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A LEAD RUBBER BEARING DEVICE EQUIPPED WITH OPTIMAL SHAPE AND RUBBER MATERIAL

Natalia Lasowicz[1], Neda Asgarkhani[1], and Farzin Kazemi[1]

[1] Faculty of Civil and Environmental Engineering, Gdańsk University of Technology, ul. Narutowicza 11/12, 80-233 Gdansk, Poland

e-mail: {natmajew, neda.asgarkhani, farzin.kazemi}@pg.edu.pl

Abstract

Earthquake induced vibrations are one of the most dangerous and unpredictable loads that can act on civil engineering structures. The lead rubber bearing (LRB) is energy dissipation device to decrease the earthquake loads on top structure and dissipate it before more failure on structural elements. The LRB is designed to increase the fundamental period of structure and allows the structure to sway on the bottom but not in each floor levels. Therefore, the interstory drift ratio is reduced and improves the performance of structure. The limitation on the sway distance could prevent the better performance of LRB, however, this research aims to investigate the effectiveness of different rubber materials, shape of LRB, and LRB layer number under different cyclic loads to propose the optimal sway distance. The numerical models are verified in ABAQUS software. The results show that application of an appropriate ratio of rubber to steel layer thickness in the construction of LRB may increase the area of the loops of the hysteresis curve what result in increase in the dissipated energy of even around 24.0%. In addition, lead core bearings significantly increased damping compared to laminated rubber bearings. Increasing yield strength of the core by 102% result in an increase in dissipated energy increase of approximately 91.9%.

Keywords: Lead Rubber Bearing, Computational Methods, Retrofitting Structure, Finite Element Model, Rubber Material Model.

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1 INTRODUCTION

Seismic excitations may cause unpredictable and dangerous situations for civil engineering structures [1, 2]. To avoid such situation different approaches were investigated to improve the seismic resistance of structures. One of them took into account an increase in resistance capacity of the building by using reinforces concrete shear walls [3], lateral bracing systems [4] and moment-resistant frames [5, 6]. However, this solution result in relatively high costs associated with the construction of these structures and it is also not possible to increase stiffness indefinitely. In the case of newly designed or even damaged building, an idea of application additional devices in the form of bracing members so as to increase energy dissipation was proposed [7]. Moreover, the novel retrofitting methods have been proposed to improve the seismic performance of buildings while keeping them in proper life-safety level.

Another method that was introduced and is very commonly used is application of base isolation that can reduce forces transmitted from the ground to the structure by installation of different type of base isolators between the building and its foundation [8]. Nowadays very often used isolators are lead rubber bearings (LRBs). Such device was design in such a way to ensure desired lateral flexibility, a sufficient vertical stiffness and a high energy dissipation capability [9-11]. The LRB is designed to increase the fundamental period of structure and allows the structure to sway on the bottom but not in each floor levels. Therefore, the interstory drift ratio is reduced and improves the performance of structure. The limitation on the sway distance could prevent the better performance of LRB.

These elastomeric bearings consist of thin laminated layers of rubber and steel plates, and lead core placed in its center. Moreover, adding in the center of LRB, a lead core resulted in significant increase in vertical stiffness and the possibility of dissipating energy [12]. LRBs due to their previously mentioned advantages and quite low maintenance costs are very commonly used as a base isolation devise in the case of building and bridges. However, the design procedure of such elements is quite complicated due to the large number of parameters that have to be taken into account. The guidelines for the design of LRB device was presented in studies [13-15], which includes the information as geometry of lead core, thickness and number of rubber layers, and their material properties that have to be introduced for estimating a desired LRB device.

The main idea presented in this paper is to investigate the effectiveness of using different rubber materials, material strength, and steel and rubber layer thickness under cyclic loading in order to propose the optimal design parameter selection of LRB. The most effective values of geometry and material parameters were proposed so as to improve the calculation and reduce its time. Having influential parameters of modeling, it would be possible to provide better illustration of LRB performance and how to control those characteristics to optimal the behavior.

2 NUMERICAL MODELS

The study has been focused on numerical analysis of LRB device to introduce a practical designing method. The 3D finite element model (FEM) of LRB was developed using solid element for steel members and hyperelastic material for rubber member in ABAQUS software. The top and bottom plates of LRB have S355 steel material [4], while the characteristics of steel core and rubber material were changed during the investigation. It should be noted that the vertical load of 667 kN was applied at the top of LRB by considering a five-story steel structure with design information provided in [16-18]. Hysteresis curve of LRB-1 and LRB-7 models were achieved as presented in Figure 1 according to a full loading protocol with four-stage displacement increment. As presented in Figure 2, which presents von-Misses stress distribution of LRB-1 model at 80 mm deformation, the von-Misses stresses in rubber layers are critical in LRB deformation and the failure of rubber layers can lead to total failure of device. However, the steel core has considerable influence on the yielding state of LRB. Considering the full loading protocol, Figure 3 presents the residual von-Misses stress in LRB-1 at the end of analysis. This confirms the stress remaining in rubber and steel layers, and further challenge the optimal selection of layer thickness.

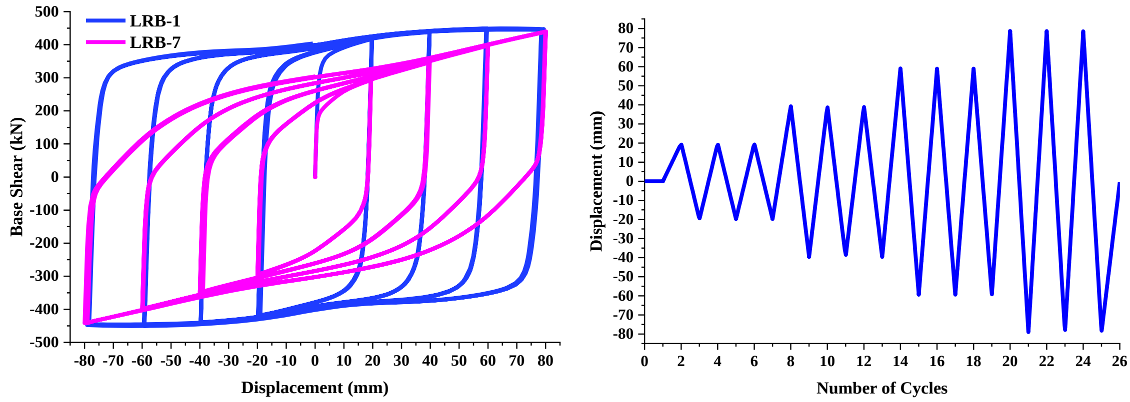

Figure 1: Hysteresis curve of LRB-1 and LRB-7 models developed in ABAQUS software and cyclic loading protocol used for analysis.

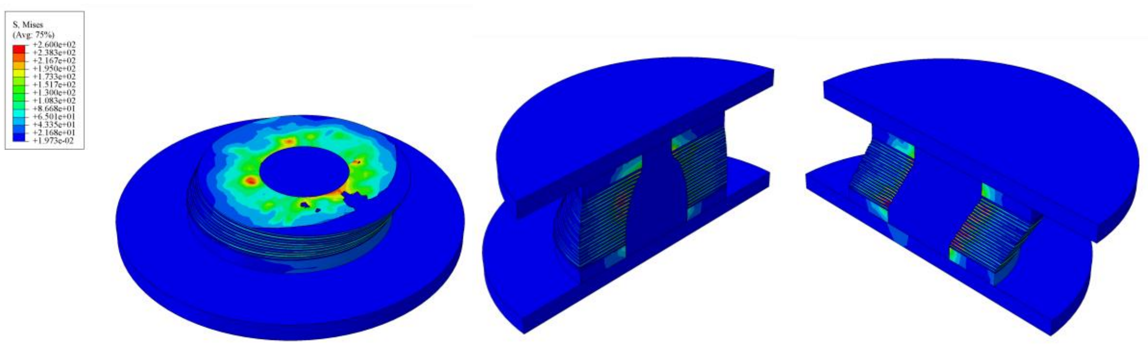

Figure 2: Von-Misses stress distribution of LRB-1 model at 80 mm deformation in loading protocol.

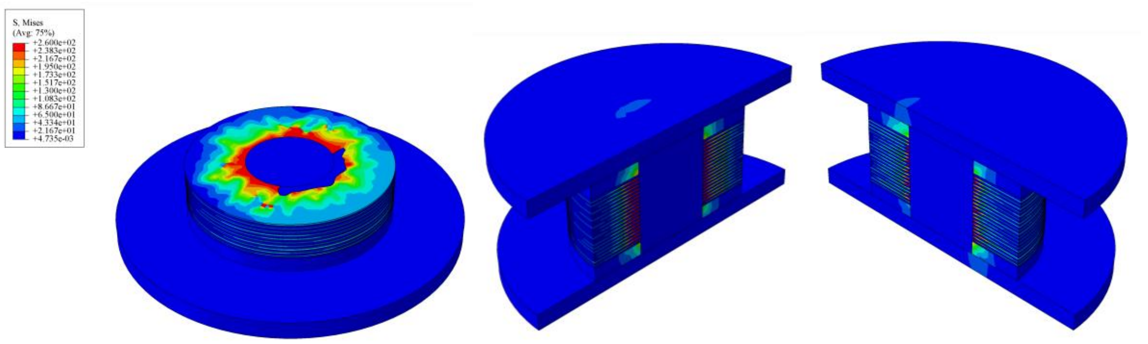

Figure 3: Residual von-Misses stress in LRB-1 at the end of loading protocol.

3 RESULTS AND DISCUSSION

3.1 Parametric analysis

In the parametric analysis, different type of rubber material described by μ (i.e., friction coefficient in sliding isolation systems in LRB) varying from 0.428 to 0.7 have been taken into account, as well as different thicknesses of rubber and steel layers have been considered. Another parameter that has been changed was λ factor that describe stiffness and strength of rubber layer. To ensure more detailed analysis, the yield strength of lead core has been increased two times in the case of LRB-7. All the examples of LRBs considered in the study have been summarized in Table 1.

Table 1: Numerical models and characteristics of LRB device.

Model	Rubber thickness (mm)	Steel thickness (mm)	μ	λ	Yield strength of core (MPa)	Dissipated Energy (one-cycle) (kJ)
LRB-1	4	3	0.428	3.91	19.6	72.447
LRB-2	5	2	0.428	3.91	19.6	63.757
LRB-3	6	1	0.428	3.91	19.6	58.438
LRB-4	6	1	0.6	3.91	19.6	58.417
LRB-5	4	3	0.7	3.91	19.6	57.923
LRB-6	4	3	0.55	3.91	19.6	72.233
LRB-7	6	1	0.428	3.91	39.6	112.158
LRB-8	6	1	0.428	2.0	19.6	58.204
LRB-9	5	2	0.5	3.91	19.6	63.930
LRB-10	4	3	0.5	3.91	19.6	71.961

A large number of detailed numerical analysis have been considered during numerical investigation. The most representative ones have been described in details in this section. The hysteretic behavior of LRBs has been investigated under one-cycle loading. The displacement amplitude was adopted as 50 mm. In the first parametric analysis, three type of LRBs (i.e., LRB-1, LRB-2 and LRB-3) characterized by constant value of μ and λ, but different thicknesses of rubber and steel layers have been tested numerically. The results of this consideration in the form of hysteresis curves have been presented in Figure 4. It can be seen in Figure 4 that the LRB-1 has larger loops and a steeper second slope compared to LRB-2 and LRB-3, what indicates that application of 4:3 ratio of rubber to steel layer thickness in the construction in LRB-1 increases the loops of the hysteresis curve. The increase in the area of the loops of the hysteresis curve observed together with the increase in the thickness of steel layers and the reduction of the thickness of the rubber layers result in increase in the dissipated energy.

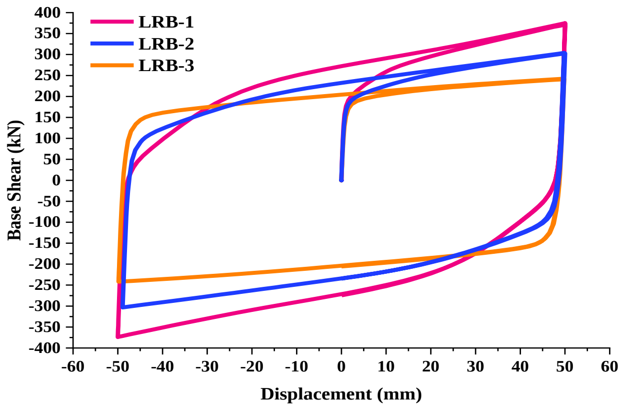

Figure 4: Comparing LRBs with different steel and rubber thicknesses in one-cycle loading.

The dissipated energy in each loop of the hysteresis curve was determined for LRB-1, LRB-2 and LRB-3. The energy dissipated by LRB-1 amounts to 72.477 kJ, while for LRB-2 it is 63.757 kJ and for LRB-3 is equal to 58.438 kJ. It can be seen that increasing the thickness of the steel layers by 1 mm and reducing the thickness of the rubber layers by 1 mm result in an increase in dissipated energy by 8.72 kJ (comparing LRB-2 to LRB-1), representing a percentage increase of approximately 13.6 %. Increasing the thickness of the steel layers by 2 mm and reducing the thickness of the rubber layers by 2 mm to LRB-3 result in an increase of dissipated energy by 14.039 kJ compared to LRB-1, which indicates a percentage increase of around 24.0 %. Moreover, it can be observed from Figure 4 that in the case of LRB-1 the maximum value of the shear force is achieved 374.92 kN, while for LRB-2 is equal to 304.01 kN, and for LRB-3 decreased to 242.14 kN. Taking into account LRB-3, it can be concluded that increasing the thickness of the steel layer by 1 mm and reducing the thickness of the rubber layer by 1 mm in LRB-2 affects the increase of the shear force by 26 %, while increasing the steel layer by 2 mm and reducing the thickness of the rubber layer by 2 mm gives an increase of 55 %.

In the second step of parametric investigation, those LRBs with the same rubber and steel layer thicknesses, constant value of λ but different values of μ have been considered. Taking into account those assumptions hysteresis curves for LRBs have been determined. Then, hysteretic behavior under one-cycle loading in each pair has been compared (i.e., LRB-1 with LRB-10, LRB-2 with LRB-9, and LRB-3 with LRB-4).

It should be underlined that negligible changes in the shape of the hysteresis curves estimated for LRB-1 and LRB-10 were observed (see Figure 5), they are almost identical. Moreover, determined values of dissipated energy of the compared devices and the value of the shear base force achieved by them are almost at the similar level. The energy dissipated by LRB-1 amounts to 72.477 kJ, while for LRB-10 is equal to 71.961 kJ. It can be seen that increasing μ from 0.428 to 0.5 result in a slight decrease in dissipated energy by 0.516 kJ, representing a percentage decrease less than 1%. Almost identical conclusions can be drawn by comparing LRB-3 with LRB-4. Similar slight decrease in dissipated energy by less than 1% was observed by changing μ from 0.428 to 0.6, while in the case of LRB-2 and LRB-9, a slight increase was observed.

Figure 5 illustrates also base shear force, which for example for LRB-2 and LRB-9 are equal to 304.10 kN and 307.63 kN, respectively. Such a slight increase around 1% of the base shear force can be observed in the case of higher value of μ (i.e., 0.5) in the case of LRB-9. The maximum value of base shear force estimated for LRB-3 amounts to 242.14 kN, while in the case of LRB-4 it is equal to 248.77 kN. Changing of μ from 0.423 (i.e., LRB-3) to 0.6 (i.e., LRB-4) result in a slight increase of maximum base shear force (by 3%). It should be noted that changing μ from 0.428 to 0.6 has no influence on hysteretic behavior of LRBs which rubber and steel layer thickness are the same.

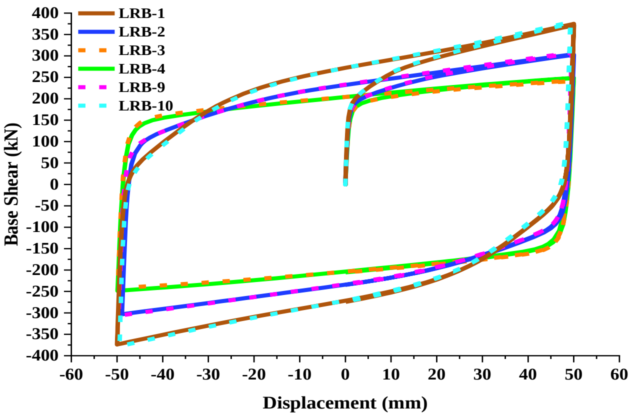

Figure 5: Comparing LRBs with different μ values in one-cycle loading.

Another numerical consideration has been focused on following LRB-3 and LRB-8 devices. Those LRBs were characterized by the same geometrical characteristics and constant value of μ, only λ in the case of LRB-3 was equal to 3.91, while in the case of LRB-8 amounted 2.0. Figure 6 illustrates comparison of hysteretic behavior of LRB-3 with LRB-8 characterized by different λ values in one-cycle loading. In the Figure 6, negligible changes in the shape of the hysteresis curves estimated for LRB-3 and LRB-8 were observed. Comparing base shear force obtained for each LRBs and values of dissipated energy no significant changes were noticed. It should be underlined that changing λ from 2.0 to 3.91 has no influence on hysteretic behavior of LRBs.

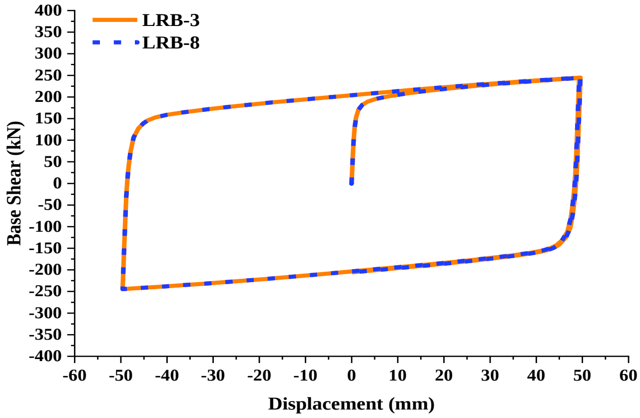

Figure 6: Comparing LRBs with different λ values in one-cycle loading.

Last analysis has been devoted to LRBs with different yield strength of cores in one-cycle loading. LRB-3 and LRB-7 that consist of 6 mm rubber layer and 1 mm steel plate thickness, μ =0.428, and λ =3.91 were considered. However, they differ in the yield strength of core that was assumed 19.6 MPa and 39.6 MPa for LRB-3 and LRB-7, respectively. It can be seen in Figure 7 that change in yield strength of lead core has a significant impact on hysteretic behavior of LRBs. The energy dissipated by LRB-3 amounts to 58.438 kJ, while for LRB-7 is equal to 112.158 kJ. Therefore, increasing yield strength of lead core by 102% result in an increase in dissipated energy by 53.72 kJ, representing a percentage increase of approximately 91.9%.

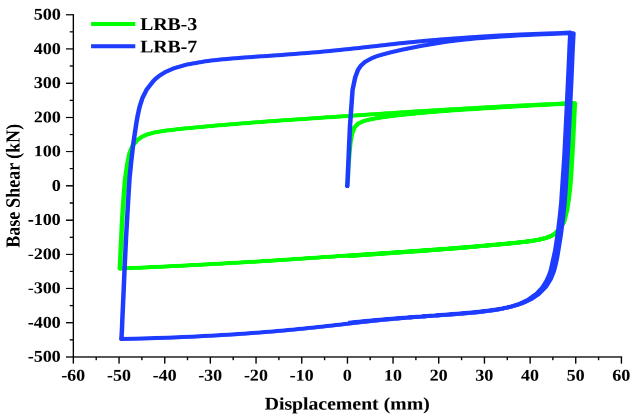

Figure 7: Comparing LRBs with different yield strength of cores in one-cycle loading.

3.2 Design recommendations for numerical modeling of LRB

Although considering many numerical models can lead to a clear trend of each parameter, the study selected only those influential LRB models to present the trends of LRB characteristics. Since the study used numerical modeling in ABAQUS software, it should be recommended to take the possibility of differences with real-world behavior of LRBs, and validate the modeling before taking those parameters into account. Due to time consuming analysis of LRB, one-cycle loading protocol was used for parametric study, however, the results and changing parameters are hold true for full-cyclic loading.

4 CONCLUSIONS

This study has been focused on numerical investigation of the effect of different rubber materials, steel and rubber layers, and steel material strength of LRB under different cyclic loading so as to propose a practical designing method. For this purpose, 3D FEM models of LRB have been created in ABAQUS software using solid element and hyperelastic material. Geometrical and mechanical characteristics of steel core and rubber material have been changed during the numerical study. The hysteretic behavior of different models of LRBs under one-cyclic load have been analyzed. The results are concluded as follows:

- Application of an appropriate ratio of rubber to steel layer thickness in the construction of LRB may increase the area of the loops of the hysteresis curve what result in increase in the dissipated energy. Using a 4:3 ratio of rubber to steel thickness in LRB-1 result in an increase in dissipated energy by 8.72 kJ, representing a percentage increase of approximately 13.6% compared to the 5:2 ratio used in the LRB-2. Moreover, comparing LRB-1 with LRB-3, where 6:1 ratio of rubber to steel thickness was used, an increase in dissipated energy by 14.039 kJ can be observed, indicating a percentage increase of around 24.0%.
- Application of an appropriate ratio of rubber to steel layer thickness in the construction of LRB may increase the maximum value of the shear force achieved at the base. Taking into account LRB-3, it can be concluded that increasing the thickness of the steel layer by 1 mm and reducing the thickness of the rubber layer by 1 mm in LRB-2 affects the increase of the shear force by 26%, while increasing the steel layer by 2 mm and reducing the thickness of the rubber layer by 2 mm (LRB-1) gives an increase of 55%.
- Application of rubber materials with different values of friction coefficient from 0.428 to 0.7 result in negligible changes in the shape of the hysteresis curves, they are almost identical. Moreover, determined values of dissipated energy of the compared devices and values of the shear base force achieved by them are almost at the similar level. These differences are less than 1%.
- Changing λ factor that describes stiffness and strength of rubber layer from 2.0 to 3.91 has no influence on hysteretic behavior of analyzed LRBs.
- Changing yield strength of a lead core has a significant influence on hysteretic behavior of LRBs under one-cycle loading. Increasing yield strength of the core by 102% (from 19.6 MPa to 39.6 MPa) result in an increase in dissipated energy increase of approximately 91.9%.

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