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EFFECT OF NUMBER OF RUBBER LAYERS, CORE RADIUS AND LEAD TYPE ON LEAD-CORE RUBBER BEARINGS' PERFORMANCE

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ABSTRACT: This research conducts a sensitivity analysis on the mechanical properties of lead core rubber bearings (LCRBs). Here, the input variables include: number of rubber layers, lead core radius and lead core material properties. A full-factorial experiment is designed and the hysteretic behaviour of designed LCRBs with varying parameters is captured through numerical simulation. The material models used in the numerical models were first validated with experimental results. The effectiveness of the studied bearings is examined by studying their horizontal stiffness. An analysis of variances is then conducted in order to quantitatively express the effectiveness of each parameter. Among the three considered input variables, the lead core radius is the most dominant parameter in affecting LCRBs' performance, whereas the number of rubber layers has the least contribution. It is observed that the lead core influences bearing stiffness the most, compared to the other input variables.

1. Introduction

Isolation techniques help buildings, bridges and other structures operate safer and withstand stronger earthquakes where they have been used since as early as 1970s (Hwang and Chiou 1996). For the past three decades, different isolation devices have been introduced and implemented in real-life practice and have been successful in terms of saving structures from severe damages (Jangid and Datta 1995; Kelly 1986). Base isolation systems are intended to shift the natural frequency of the structure far enough from the excitation frequency, as a consequence of which the structure will experience less structural and non-structural damages. Base isolators are used for a wide range of purposes. They are not only used to decouple the structure from ground vibrations, but also are implemented to accommodate pre-stressing relaxations, thermal movements, shrinkage and time-dependent phenomena such as creep (Cardone and Gesualdi 2012; Mitoulis et al. 2010).

Different types of isolators are introduced for isolation purposes (e.g., friction-based and elastomeric isolators). In this study, a brief literature review focusing on elastomeric isolators is given. Performance of lead-core rubber bearings (LCRBs) is investigated through numerical study using material properties validated with experimental results. The effects of three input variables including the number of rubber layers, lead plug radius and lead core material properties are studied for a full-factorial design configuration (Hedayati Dezfuli and Alam 2013). The effects are shown in terms of bearings' operational characteristic, the horizontal stiffness. A sensitivity analysis is conducted in order to quantitatively express the results (Hedayati Dezfuli and Alam 2014). Hysteretic behaviour of bearings is captured under different shear strain levels. Hysteretic damping ratio provided by the bearing is also acquired and a comparison is drawn in order to highlight the effect of each parameter. Finite element method is used to conduct the aforementioned analyses and Analysis of Variances (ANOVA) is implemented to interpret the results.

2. Lead-core rubber bearings (LCRBs)

Isolation bearings have to exhibit three main features: 1) a desired lateral flexibility, 2) a sufficient vertical stiffness and 3) good energy dissipation capability. In regular rubber bearings, these three responsibilities are carried out by rubber and steel shims. However, adding a lead plug to the bearing system augments its performance significantly. The lead plug contributes to a higher vertical stiffness. Besides, it enhances the energy absorption capacity and adds hysteresis damping to the system as it undergoes inelastic deformation. As the lead plug goes beyond elastic deformation, structure's stiffness decreases and, as a consequence, the natural period of the structure, which is inversely related to the stiffness, increases. The lead plug also offers an added initial rigidity to the structure to more effectively resist wind loads and minor earthquakes.

LCRBs are efficient in terms of initial and maintenance costs among passive isolating systems. This fact gives rise to their applicability and makes them more widely accepted (Makris and Chang 1998). They have been used in bridges since 1978 (Hwang and Sheng 1994) and were implemented in buildings for the first time in New Zealand (Jangid 2007). LCRBs' decent characteristics have made them reliable enough to be implemented in various types of structures such as multi-storey buildings (Islam et al. 2012), highway bridges (Ghobarah and Ali 1990; Tan and Huang 2000; Turkington et al. 1989), railway bridges (Xu et al. 2011) and even more strategic infrastructures like nuclear power plants (Kumar et al. 2014).

Lead-core rubber bearings are studied from different viewpoints. For example, Zordan et al. dealt with the evaluation of the equivalent viscous damping associated with lead rubber bearings to predict the deformation demands of isolated structures (Zordan et al. 2014). Xu et al. studied the effect of mechanical parameters of lead-rubber bearings such as yield strength, initial shear stiffness and hardening ratio and found them highly important for the isolator's performance (Zhao et al. 2011). Ozdemir et al. tracked the change in lead-rubber bearings' performance due to heating of the lead core as it goes through numerous cycles (Ozdemir et al. 2011). Design procedures have also been suggested for LCRBs (Islam et al. 2013). However, limited research has so far been conducted focusing on the performance sensitivity of such bearings to their mechanical and material properties. Therefore, a sensitivity analysis will be performed in this study.

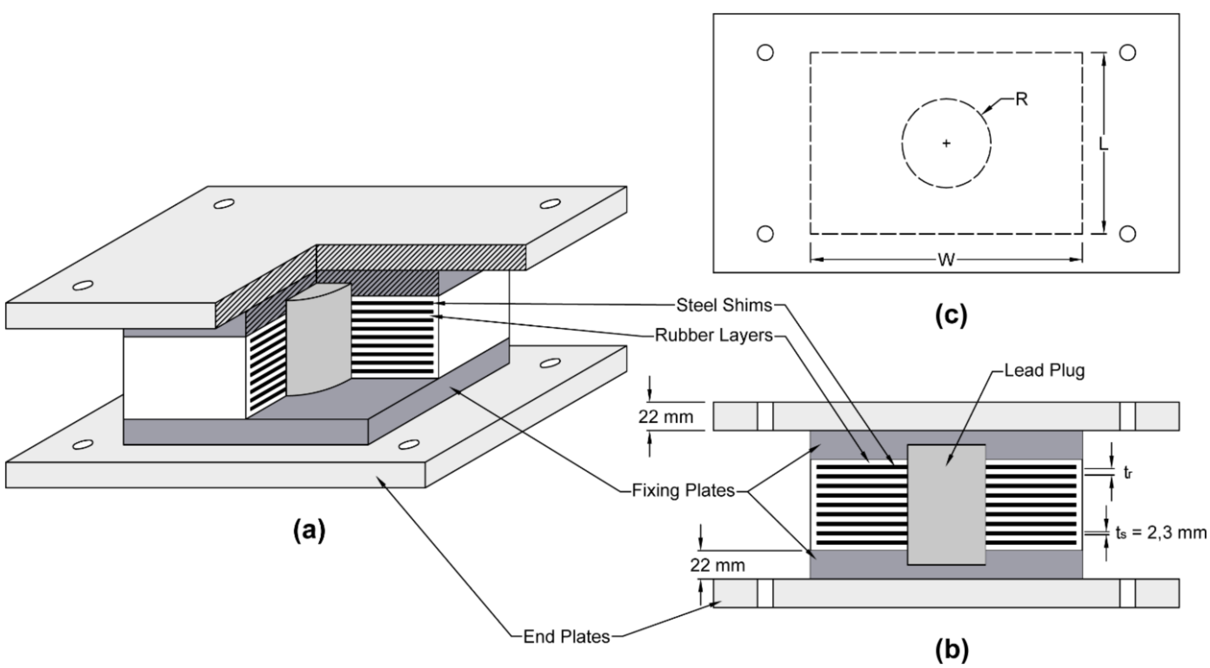

Figure 1. Schematic view of (a) lead-core rubber bearing and its components, (b) Side view and (c) Plan view

The schematic view of a lead-core rubber bearing is shown in Figure 1. Figure 2 illustrates a typical mechanical model representing the hysteresis behaviour of LCRB. This hysteresis curve represents how the bearing behaves when subjected to cyclic shear loadings. Important characteristics are extracted from this curve, including bearing's initial, post-yield and equivalent stiffnesses (K_i, K_p and K_{eq}, respectively). The bearing's yield displacement, x_y, the elastic and dissipated hysteretic energies (E_S and E_H), the hysteretic viscous damping ratio, ξ_H, and the bearing's characteristic strength Q_y are also found from this curve. The hysteretic damping ratio is considered as the ratio of the energy dissipated per cycle to the elastic strain energy as follows:

$$\xi_H = \frac{E_H}{4\pi E_S} \tag{1}$$

Among the aforementioned parameters, the yield displacement, the post-yield stiffness and the characteristic strength are sufficient to define the bi-linear force-displacement behaviour model of a lead-core rubber bearing (Matsagar and Jangid 2004). These parameters are illustratively shown in Figure 2.

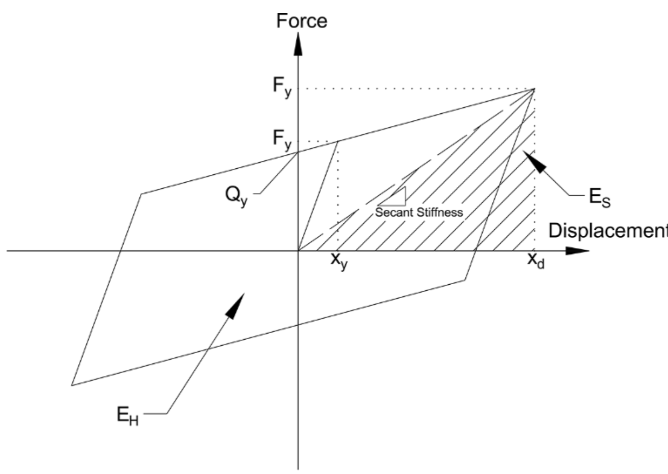

Figure 2. Idealized bilinear mechanical hysteresis model of LCRB

2.1. Validating the rubber material model

Material properties of elastomer parts incorporated in the bearing are of significant importance and need to be modeled carefully. The elastomer parts include the rubber layers themselves and the cover layers surrounding steel shims (see Figure 1(a)). The material properties chosen to be used for modeling these layers should be capable of demonstrating rubber material behavior for a wide range of shear strains. One specific feature of rubber-like materials (elastomers) is undergoing large deformations with small volume changes ("ANSYS Documentation" 2006). That is the property, which causes the rubber to have high compressive stiffness along with high lateral flexibility simultaneously. A common practice is to use hyper-elastic material models for modeling these types of materials in conjunction with viscoelastic ones, as is the case in this study. To this end, a 3-parameter Mooney-Rivlin material model is used to simulate the hyper-elasticity of rubber and a Prony material model is considered to model its viscoelastic shear response.

To prove the accuracy of the material model used for rubber, simulated behavior is compared to that of an experimental investigation conducted on lead-core rubber bearings as shown in Figure 3 (Abe et al. 2004). Dashed lines in this figure represent the experimental data and solid ones are obtained using current numerical simulation. As observed, the implemented material model is capable of capturing rubber's behavior with excellent accuracy. In terms of energy dissipation capacity, which is one of the main objectives studied in this research, the theoretical model predicts the experimental data with a variation of less than 5%. The variations observed mostly in negative shear strains are due to difficulty of applying perfect symmetry conditions in real-life experiments. Rate-dependent properties of rubber can also be introduced as another source of this variation, which is an inevitable characteristic of such hyperelastic-viscoelastic models (Bhuiyan and Ahmed 2007; Khajehsaeid et al. 2014).

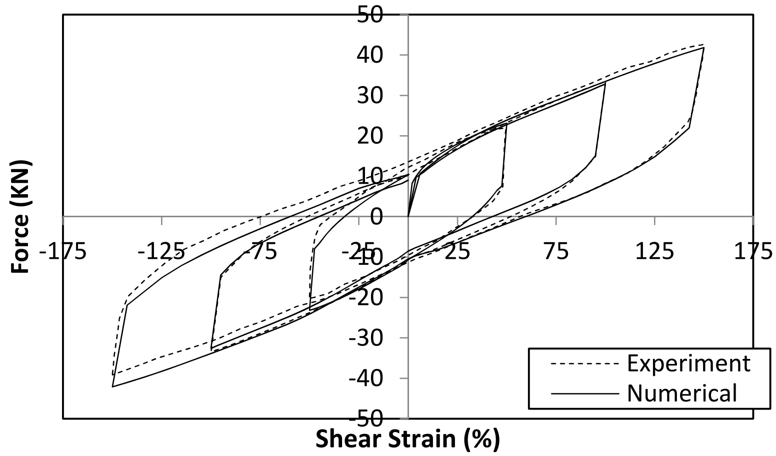

Figure 3. Rubber numerical material model validation with experimental results by (Abe et al. 2004)

3. Sensitivity Analysis

Various physical and mechanical parameters as well as material properties affect the performance of lead-core rubber bearings. A number of parameters are explained in order to illustrate their influence. Among physical characteristics, height of the rubber bearing can be mentioned as one important factor, directly affecting the lateral flexibility of the isolator. Isolator's height is usually governed and limited by substructure type and the available space. However, the effective height of rubber bearing (height of the laminated pad without supporting end plates) depends on the number of rubber layers and steel shims, as well as their thicknesses. Supporting and fixing steel plates are assumed to be rigid enough, in comparison to rubber, in order not to affect bearing's lateral flexibility. Their only contribution is to, respectively, support and fix the laminated pad. Considering the laminated pad the only member taking part in providing the lateral flexibility, the equation to obtain the effective height, H_e, can be written as:

$$H_e = n_r \times t_r + n_s \times t_s \quad (8)$$

in which n_r, t_r, n_s and t_s represent the number of rubber layers, the thickness of rubber layers, the number of steel shims and the thickness of steel shims, respectively. Number of steel shims is governed by that of rubber layers ($n_s = n_r - 1$). Their thickness is also much lower than that of rubber layers. The effect of thickness of steel shims on the bearing's performance was studied and found to be not remarkable, compared to that of elastomer layers. Thus, keeping steel shims' thickness constant, equation (8) can be re-written in order to express the thickness of rubber layers, t_r, in terms of the effective height and the number of rubber layers as follows:

$$t_r = \frac{H_e - (n_r - 1) \times t_s}{n_r} \quad (9)$$

Figure 1 shows the arrangement of rubber, steel shims, fixing plates and supporting end plates, forming the rubber bearing. Table 1 also shows dimensions and parameter values of considered LCRBs.

Table 1. Parameters and dimensions of LCRBs

Parameter	***Symbol***	***Value***
Bearing length	L	$210\ mm$
Bearing width	W	$210\ mm$
Lead plug radius	R	Varies, as in Table 2
Number of rubber layers	n_r	Varies, as in Table 2
Thickness of rubber layers	t_r	Varies, as in Table 4
Thickness of steel shims	t_s	$2.3\ mm$

In addition to rubber and steel, the lead core also plays a significant role in lead-core rubber bearings. Energy dissipation capacity of the isolator is directly affected by the type and volume of lead implemented in it. These two affecting characteristics, i.e. the radius and material of lead core effects are analyzed in this research. The former represents the amount of lead implemented in the bearing and the latter demonstrates the effectiveness of lead type and its mechanical properties in LCRB.

Rate- and strain-dependency of rubber, as a hyper-elastic and viscoelastic material, make its operational characteristics reliant on loading conditions including loading frequency and amplitude. Study on these factors has been conducted during the validation process. The validated rubber material model for a specific load pattern shown in Figure 4 is used. For different load patterns and rubber materials, further study is needed to look into the effect of loading pattern on LCRBs' performance.

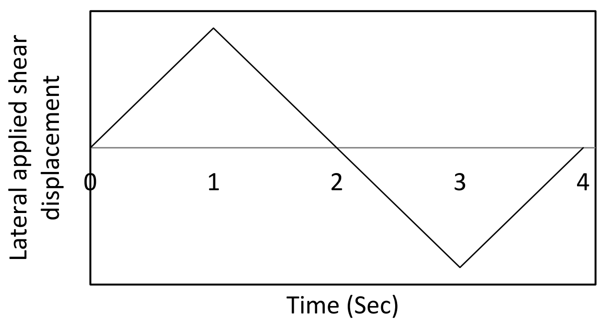

Figure 4. Applied shear loading (f=0.25 Hz and for different amplitudes of shear strain)

Lateral and vertical stiffness as well as the equivalent viscous damping are known as the operational characteristics of rubber bearing isolators, which can be used to evaluate their performance under specific loading conditions. The horizontal stiffness, K_h, has been selected to be considered in this study. A sensitivity analysis has been conducted on three of the previously-introduced parameters, i.e. the number of rubber layers, and the type (material grade) and the radius of the lead core. Other parameters, including height of the bearing, rubber material and temperature are kept constant in order to draw an even comparison between different cases. Table 2 shows the variables in this study and their corresponding levels used in the sensitivity analysis.

Table 2. Parameters and their corresponding levels in the sensitivity analysis

Factor	***Symbol***	***Levels***		
		1	***2***	***3***
Lead core radius, $R\ (mm)$	A	20	35	50
Number of rubber layers, n_r	B	8	9	10
Lead type	C	1	2	3

For each factor stated above, three levels are considered to represent the effect of each factor. The levels are chosen in such a way that they cover applicable ranges for each parameter as much as possible. Three lead types are examined as for the core of the bearing to demonstrate the effects of lead's material properties such as modulus of elasticity and post-yield stiffness ratio. Table 3 lists the three lead types used in this study along with their detailed properties. Number of rubber layers is also varied with respect to the rubber layers' thickness and the effective height of bearing. Numerical simulation is employed to conduct this sensitivity analysis, using ANSYS finite element software ("ANSYS Mechanical APDL" 2012), implementing validated material models. A shear strain of 100% is considered to elucidate bearing's performance under above-mentioned conditions. The shear strain is defined as the ratio of the lateral relative deformation of the bearing to the total height of rubber layers.

Table 3. Lead types used in the sensitivity analysis and their material properties

Lead type	***Yield strength (MPa)***	***Modulus of elasticity (MPa)***	***Poisson's ratio, ν***	***Post-yield stiffness ratio, α***
1 (Abe et al. 2004)	10.5	18,000	0.43	0.005
2 (Guruswamy 2000)	14.4	16,616	0.44	0.005
3 (Doudoumis et al. 2005)	19.5	18,000	0.43	0 (Bilinear Elasto-Plastic behaviour)

Having three factors and three levels for each factor, as presented in Table 2, a number of 27 runs is required to conduct a full factorial experiment for a single level of shear strain (3^3 full-factorial experiment design). Table 4 shows the runs conducted under each shear strain level. An analysis of variance is carried out on the outputs in order to underline the effectiveness of each factor on bearing's performance.

Table 4. Runs conducted in the 3^3-full-factorial experiment design

Run number / order	***Factor***			
	A (R, mm)	***B (n_r)***	***Resulting t_r (mm)***	***C (Lead type)***
1	20	8	5.00	1
2	20	9	4.19	1
3	20	10	3.54	1
4	20	8	5.00	2
5	20	9	4.19	2
6	20	10	3.54	2
7	20	8	5.00	3
8	20	9	4.19	3
9	20	10	3.54	3
10	35	8	5.00	1
11	35	9	4.19	1
12	35	10	3.54	1
13	35	8	5.00	2
14	35	9	4.19	2
15	35	10	3.54	2
16	35	8	5.00	3
17	35	9	4.19	3
18	35	10	3.54	3
19	50	8	5.00	1
20	50	9	4.19	1
21	50	10	3.54	1
22	50	8	5.00	2
23	50	9	4.19	2
24	50	10	3.54	2
25	50	8	5.00	3
26	50	9	4.19	3
27	50	10	3.54	3

As a summary, the process of evaluating LCRBs' performance can be introduced in three stages: 1) Design of the experiment and defining inputs and variables, 2) Numerical simulation using finite element method to obtain the operational characteristics of LCRBs as outputs of the system, and 3) Analyzing the outputs and their variances to find out how effective they are.

4. Results and discussion

Based on the analyses conducted, the horizontal stiffness of studied bearings is investigated. This operational characteristic is obtained as a function of considered variable parameters (number of rubber layers, lead core radius and lead type). Unlike the vertical stiffness, the horizontal stiffness is dependent on the shear strain level as well. Analyses are made based on the variable parameters (see Table 2) and the designed experiment (see Table 4). LCRBs' responses are captured under the horizontal shear loading pattern shown in Figure 4, producing their hysteretic behaviour. Figure 5(a), (b) and (c) show the behaviour of the studied cases. The horizontal stiffness is calculated with respect to model. It is shown that the bearing's horizontal stiffness increases with the number of rubber layers. However, once compared to other two factors, the degree of its effectiveness cannot be as that noticeable. Lead material properties also affect the horizontal stiffness. The higher the modulus of elasticity and the post-yield stiffness ratio, the higher the horizontal stiffness. Shear stiffness of the lead core is dependent on its modulus of elasticity and it will result in a higher bearing's lateral stiffness. However, among the three considered input parameters, the lead core radius is shown to have the most significant effect. Figure 6 plots the horizontal stiffness versus studied parameters. It can be observed that the displacement-dependency of rubber material properties causes the horizontal stiffness to decrease in larger lateral deformations. As it undergoes higher displacements, rubber gets more into the inelastic range and loses its stiffness more. In addition, it is found that the rate of horizontal stiffness reduction also decreases in higher shear strain levels. As observed, the number of rubber layers has the least contribution in affecting the horizontal stiffness. Although the lead type shows a higher effectiveness than the number of rubber layers, its effect is still much smaller than that of the lead plug radius.

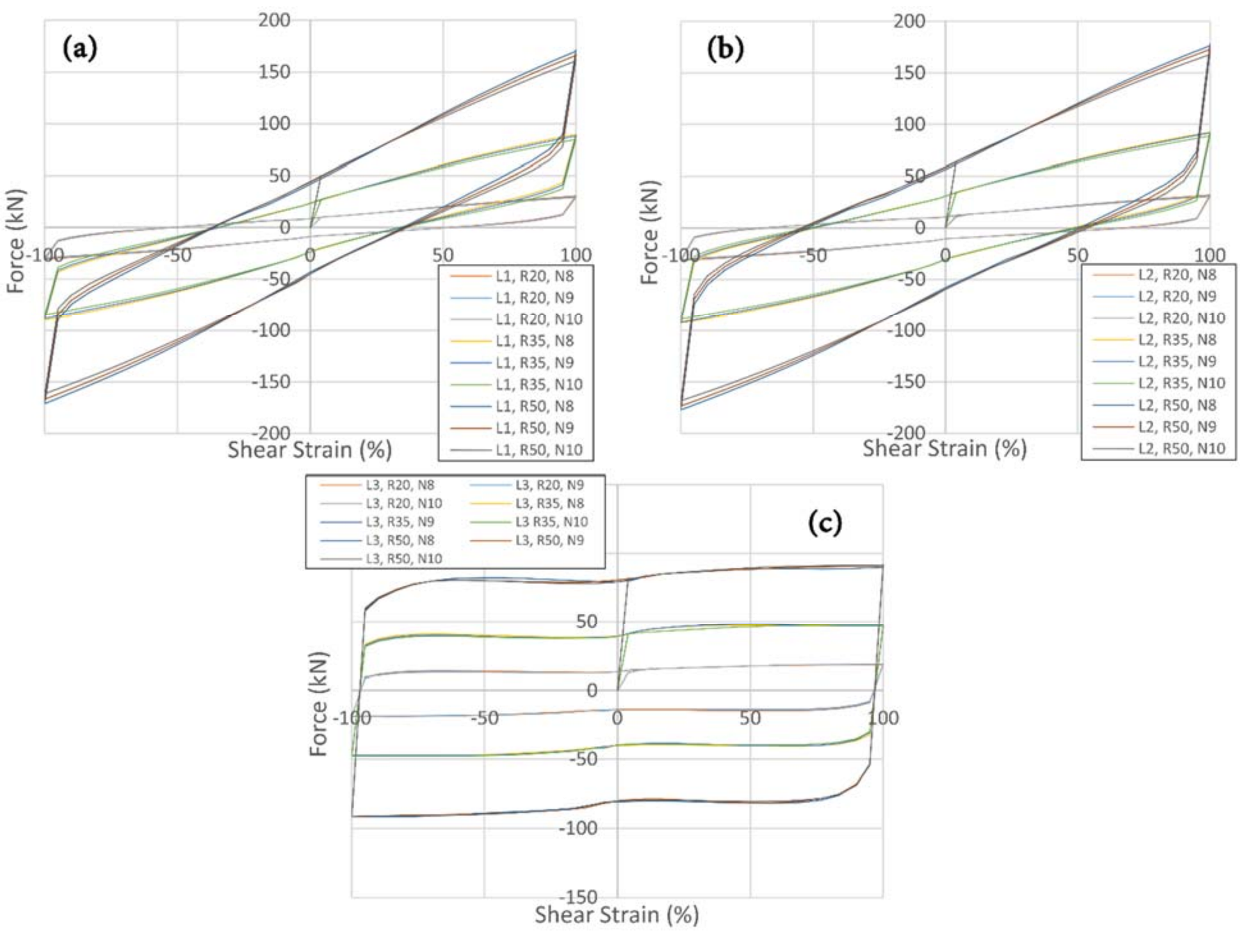

Figure 5. Shear force-strain hysteresis relationship for (a) lead type L1, (b) lead type L2 and (c) lead type L3

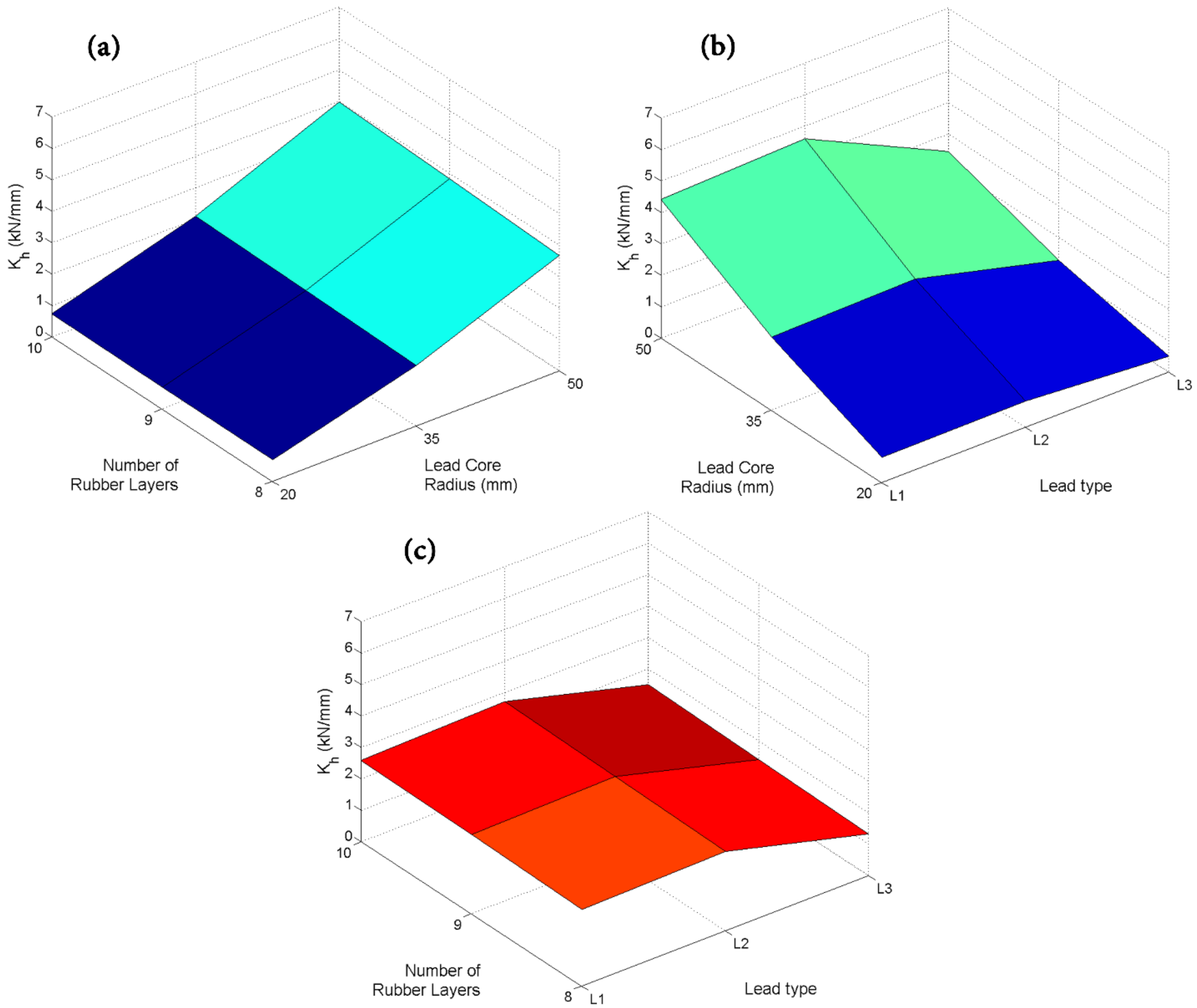

Figure 6. Horizontal stiffness versus (a) Number of rubber layers and Lead core radius, (b) Lead core radius and Lead type, and (c) Number of rubber layers and Lead type

5. Summary and conclusion

In a sensitivity analysis, the performance of lead-core rubber bearings (LCRBs) is studied as a function of three variable parameters: the number of rubber layers, lead core radius and material type of the lead plug. A validated rubber material model is used and the hysteretic behaviour of designed LCRBs is captured through numerical simulations. Bearing's performance, in terms of its horizontal stiffness, is obtained and the effectiveness of each input parameter is investigated. Based on the analyses conducted, the following conclusions can be drawn:

- Bearing's horizontal stiffness is highly dependent on lead material properties and lead plug radius.
- Lead core radius is found to be the most significant parameter. The bigger the lead plug's cross section, the higher the horizontal stiffness.
- Higher lateral displacements cause the rubber bearing to have lower horizontal stiffness which is because of rate-dependent material properties of rubber.
- Radius and material properties of lead core affect the effectiveness of the LCRB directly.
- The more strength the lead core exhibits, the higher the horizontal stiffness and, at the same time, the more energy it can dissipate through the shear deformations it undergoes.

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