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ADVANCE MODELING OF LEAD RUBBER BEARINGS UNDER HIGH STRAINS WITH EXPERIMENTAL VERIFICATION

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Abstract

Lead rubber bearings (LRBs) used for seismic base isolation system are a proven technology that adds a flexible layer at the base of the building to concentrate displacements at the base while reducing accelerations and drifts within the superstructure. Modeling of the seismic isolation system plays a key role in simulating the seismic response of base isolated buildings, including estimation of peak isolator displacement and potential to exceed the clearance to stop. Under beyond design basis shaking, seismic isolators are expected to undergo large displacements and exhibit complex behaviour. Developing accurate models of lead rubber bearings (LRB) proposed for use in buildings and other critical facilities can be challenging due to the nonlinear effects of the cyclic heating causing strength degradation and strain hardening in the rubber at large strains. A new modeling approach is proposed for simulating the cyclic behavior of LRB that aims to capture measured experimental data from full-scale bearings that display these complex characteristics. The bearing models are then applied to determine estimates of displacement and potential impact velocity to a stop or moat wall, and to identify bearing characteristic that influence the overall response of the isolated structure.

Keywords: Seismic isolation; nonlinear modeling; lead rubber bearings.

1. Introduction

Seismic isolation is an effective strategy to protect critical facilities from the damaging effects of horizontal earthquake ground shaking. The increased flexibility and resulting elongation of the natural vibration period of the structure leads to significant reductions in forces transmitted to the structure above the isolation level, at the expense of large displacements in the isolation system hardware. The seismic isolation system needs to be designed to accommodate these displacements and have the necessary horizontal clearance or moat at the basement level. The clearance is often limited by a moat wall that can also function as a stop to limit displacement and thus prevent failure of the isolation system.

Lead Rubber Bearings (LRB) are commonly used for base isolation and show complex behavior under large dynamic strains. A parallel combination of models is calibrated based on experimental data to capture the salient characteristics of LRB. To gain further insight into the complexities of LRB behavior, a brief literature review is presented. The lead plug in the LRB exhibits two phenomena's: initial lead hardening and strength degradation of the lead due to heating [1]. Initial hardening of the lead have been seen in many experiments that have been conducted on LRBs [1]–[5]. Speculations has been made for the cause of this phenomena including high speed instrument error, although the previously mentioned studies consisted of varying rates from high strain rate tests to static tests in which all showed this phenomenon. One study of only a lead specimen was tested in shear at a low strain rate also displaying this initial lead hardening phenomenon indicating that this is an inherent behavior of lead [6]. A mathematical model is later introduced to account for this phenomenon.

Rubber also contributes to the LRB's complexity, exhibiting hardening and pronounced reversal effects. Dorfmann and Ogden [7] account for this behavior due to various factors such as non-Gaussian behavior of the network chains and the degree of crosslinking, crystallization and other material related behaviors. Mullins' effect also sometimes referred to as scragging, also contributes to the hardening due to the cyclic reduction of the bulk modulus of elastomers at moderate-to-high shear strains [8]. Although Mullins' effect is essentially scragging, Clark construed this effect into two different phenomena: scragging the permanent damage of the rubber when it reaches certain strains, and Mullins' effect in which damage is accumulated as the rubber is being cycled [9]. Scragging and Mullins effect both contribute to reversal effects and need to be accounted for especially when conducting analysis of critical structures [10].

2. Parallel Numerical Bearing Models

A review of current models used for LRB indicates that state-of-the-art bearing models are only able to capture some of the LRBs complexities. This paper utilized a combination of models in an attempt to capture the key complexities observed in testing of large bearings and determine their effect on the superstructure response. The large LRBs, (total width and height of bearing being 1500mm and 561mm, respectively; lead core diameter of 320mm; height of rubber 224mm) designed for nuclear powerplants, were tested in the Seismic Response Modification Devices (SRMD) Facility at UC San Diego. The experimental data obtained from these tests were utilized for development of the parallel model. Experimental data from a wide variety of peak shear strains and strain rates were used for calibration. A brief introduction of the parallel models will be presented alongside a new phenomenological model. The parallel model is shown to give good results for 1D calibration of the parameters.

2.1 Plasticity model

The main plasticity model that is utilized for degradation of the strength of the lead and the strain hardening of lead is based on Dafalias [11].The model is modified to include heating of the lead plug as introduced in

Kalpakidis & Constantinou (2009), as shown in Equation 1. The bounding surface is a function of the temperature of the lead.

$$\boldsymbol{F}_2 = R(T_{Lt})\boldsymbol{n} - \delta\boldsymbol{\mu} \tag{1}$$

$$R = (b_1 + b_2 \cdot K_{S2} \cdot uh^2) \tag{2}$$

$$R(i+1) = R(i) \cdot \exp\left(T_{Lt}(i+1)\right) \tag{3}$$

In Eqs. (1)-(3), as the bearing is being cycled, the temperature increases using the thermal dynamic equations causing for the strength bounding surface to decrease. Parameters b_1 and b_2 are the characteristic strength and hardening of the lead, respectively. The temperature of the lead increases depending on the material and geometrical properties of the LRB. As previously mentioned, lead hardening at lower strains is also a nonlinear behavior that is seen in experimental results.

$$R = (b_1 + b_2 \cdot K_{S2} \cdot uh^2) \cdot KL \tag{4}$$

where KL,

$$KL = 1 - c_5 \cdot e^{-c_6 \cdot DL} \tag{5}$$

In Eqs. (4) and (5), the bounding surface is further modified to include a lead hardening phenomenological model. DL is the total distance travelled and increases with the accumulation of increase in displacement. Parameters c_5 and c_6 are calibrated from experimental data with the former ranging from zero to one (representing initial characteristic strength) and the latter being any positive number resulting in the rate of increase of the lead strength. For example, c_5 calibrated to 0.5, the strength of lead is initially at half its strength and as DL increases KL will increase to one, representing the full strength of the lead.

2.2 HDR Element

The HDR element introduced by Grant [12] was intended to model high damping rubber bearings. The model consists of the a hyperelastic model and a plasticity model that are able to capture nonlinearities in a HDR bearing. This model is used in parallel to capture the previously mentioned complexities and further explained in the following sections.

2.2.1 Hyperelastic model

The hyperelastic model is considered for the parallel model to capture the strain hardening effects. This model consists of a hyperleastic model and the previously mentioned plasticity model. The model is also able to account for Mullins effect and scragging effects.

2.2.2 Plasticity (Reversal) model

The plasticity model is considered in the parallel system to account for the reversal effects. The model, shown in Eq. (1) (without any lead heating), is used with certain input parameters in order to capture the reversal effects that are exhibited in experimental results.

3. Calibration of Parallel System (Nonlinear LRB Model)

A parallel system consisting of the models described earlier is calibrated in order to capture the different complexities observed in LRB including lead hardening (LH), lead heating, and reversal effects. As shown in Fig. 1a, the heating model is able to capture the strength degradation effects. It is also able to capture the lead hardening effect as can be seen by comparison to the model without LH effect in Fig. 1b. It is also noted that the heating model without lead hardening initially overestimates the characteristic strength of the LRB.

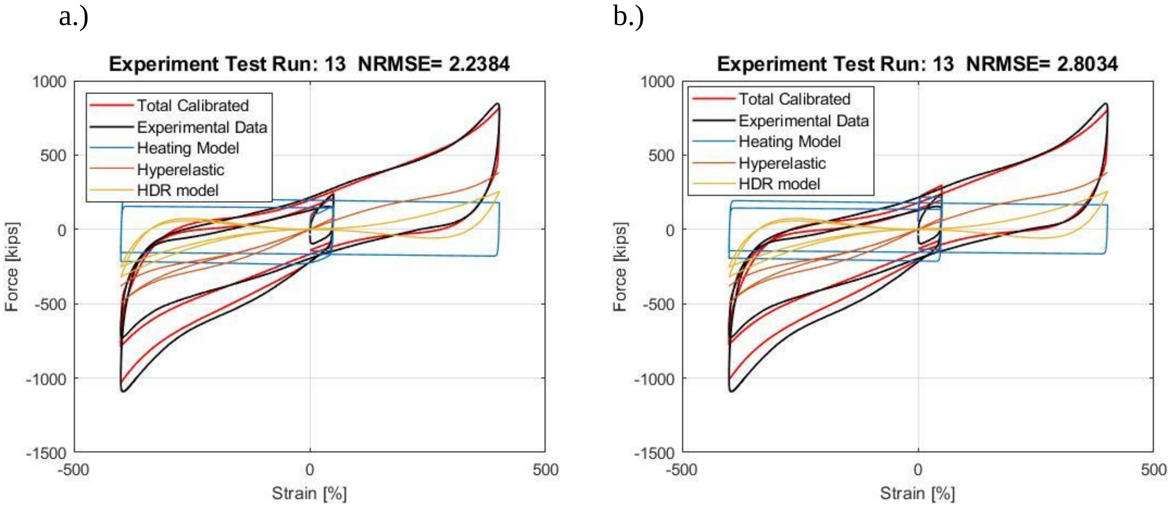


Fig. 1 - Parallel System: Contributions of Parallel System.

In order to calibrate model parameters based on the available experimental data, the initial design values from the manufacture were first set as preliminary parameters then the *fminsearch* function in Maltab was utilized to perform the calibration as shown in Table 1. The error measure used was the Normalized Root Mean-Squared Error (NRMSE). The NRMSE is calculated using the difference of the experimentally measured force and the numerical force determined numerically using *OpenSees* and normalizing by the range of the maximum and minimum forces of the experiment. One set of parameters is desirable for the available test data covering a wide range of strains. Using a multi-objective function, the NRMSE is minmized to obtain one set of parameters for all tests simultaneously. As seen in Eq. (6), the tests shown in Table 2 are considered when minimizing the objective function. The weights were set to be all equal and the summation equal to one. This calibration was conducted for different 1D strain and strain rate tests, results are shown in Table 2. The results and contributions of the Nonlinear LRB model for test 13 can be seen in Fig. 1a.

Table 1 - Preliminary properties

K_{ini} (kN/m)	2524.65
F_y (kN)	936.35
Post elastic over elastic stiffness ratio	0.0072
Height of rubber (m)	0.224

$$\epsilon = \sum_{i=1}^{no.\,tests} (w_i NRMSE_i) \tag{6}$$

Table 2 - NRMSE for Experimental Tests (Nonlinear LRB).

Test (#)	**Strain (%)**	**Type**	**NRMSE (%)**	**NRMSE (%) woLH**
12	100	1-D	4.63	5.52
8	200	1-D (GM)	5.38	5.29
11	300	1-D	2.98	3.64
13	400	1-D	2.24	2.80
15	500	1-D	2.63	3.01

4. Seismic Analysis of an Archetype Nuclear Power Plant

The calibrated bearing models were implemented in the APR 1400 ANT (Archetype Nuclear Test) model of a full Nuclear Power Plant (NPP) in *OpenSees* to conduct simulations under 1D seismic excitation. The reader is referred to previous studies that have been conducted on the ANT model varying from hybrid testing considering experimentally measured bearing behavior [13], sensitivity studies [14] and moat wall impact studies [15]. In order to understand the contribution of the Nonlinear LRB system, the proposed parallel model was compared to popular models including the bilinear model and the LRX which is a bilinear model with strength degradation from heating. Simulations of the ANT model are considered using the proposed model and these two models. As shown in Fig. 2, the average impact velocity at different shear strains and subsequent impacts are compared. It can be seen that the proposed Nonlinear LRB is essentially bounded by the upper and lower bounds, but the standard deviation of the impact velocities exceeds past those of the heating model for Clearance to Stop (CS) of 300 to 350% shear strain. For some cases the model is not being bound by the heating and bilinear model. This can be important when considering the ideal location for the moat wall to be placed. This is true for the second impact as shown in Fig. 2a at CS of 375% shear strain results the largest reduction in impact velocity per 25% increase in CS and this may be important when considering the importance of the superstructure's contents depending on the sensitivity of the equipment, as will be shown in a later section. This is especially important since second impact have been found to be more significant in superstructure peak accelerations [16]. Mitigating these rebound impacts by implementing these Nonlinear LRB models or purposely engaging these nonlinear behaviours may reduce rebound effects and impact velocities. Another key finding is the for the second impact, the impact is reduced more significantly compared against the heating model when comparing first to second impact. This may be due to the energy dissipation that is incurred in the Nonlinear LRB model from its pronounced reversals when rebounding for second impact.

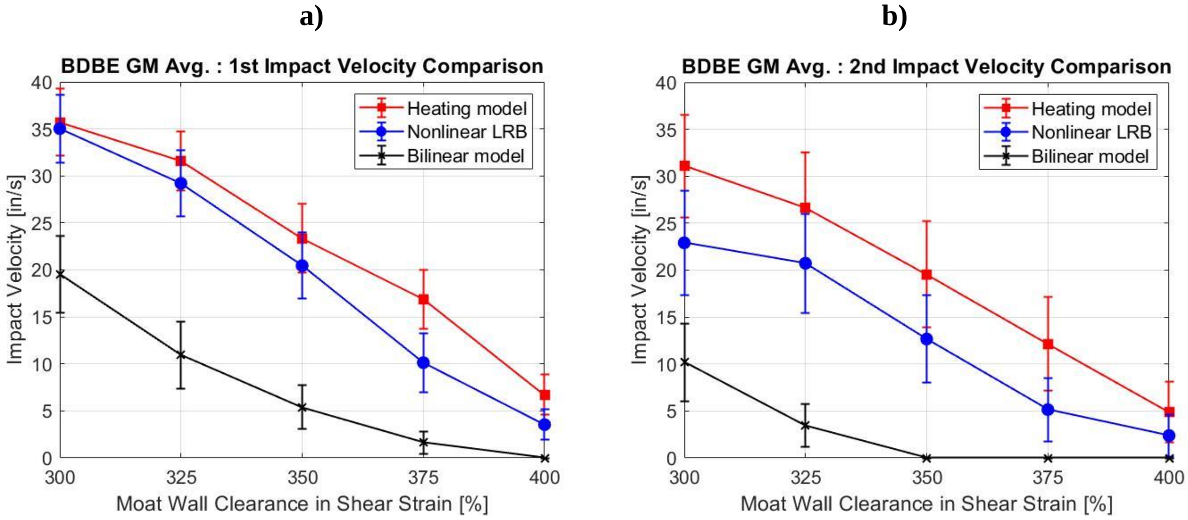


Fig. 2 - Avg. Impact Velocity vs Moat wall clearance: **a)** 1st impact **b)** 2nd impact

In Fig. 3, the average pseudo response spectra are obtained for 20 different ground motions for three different systems the heating (LB), the bilinear case (UB) and the Nonlinear LRB system. At the fundamental frequency of the Reactor Containment Building (RCB) of 2.5hz, for the CS of 300% shear strain, resulted in the average pseudo response spectra for both the Nonlinear LRB model and the LRX model being equivalent. This may be due to the fact that the hardening effect is not being fully engaged at this clearance. Another observation is that the bilinear model significantly reduces the average spectra accelerations for all frequencies. Correlation between the impact velocities and the floor response spectra are clear when comparing Fig. 3 and Fig. 4. At CS of 300% shear strain, the impact velocities are essentially equal this is evident in the response spectra. For impact velocities the Nonlinear LRB model resulted in individual cases of impact velocities exceeding those of the heating model, similarly the floor response spectra for individual earthquakes also resulted in larger floor response pseudo accelerations. For the case CS of 375% shear strain, the reduction of average pseudo accelerations for the height of 331.3 ft is ~50% from 6.5g to 3.3g. The LRX only model only reduces demands by 20% from 6.5g to 4.3g. The large reductions in the Nonlinear LRB model are due to the hardening and reversal effects that are more engaged as higher strains are attained before impact, reducing impact velocities and average pseudo accelerations.

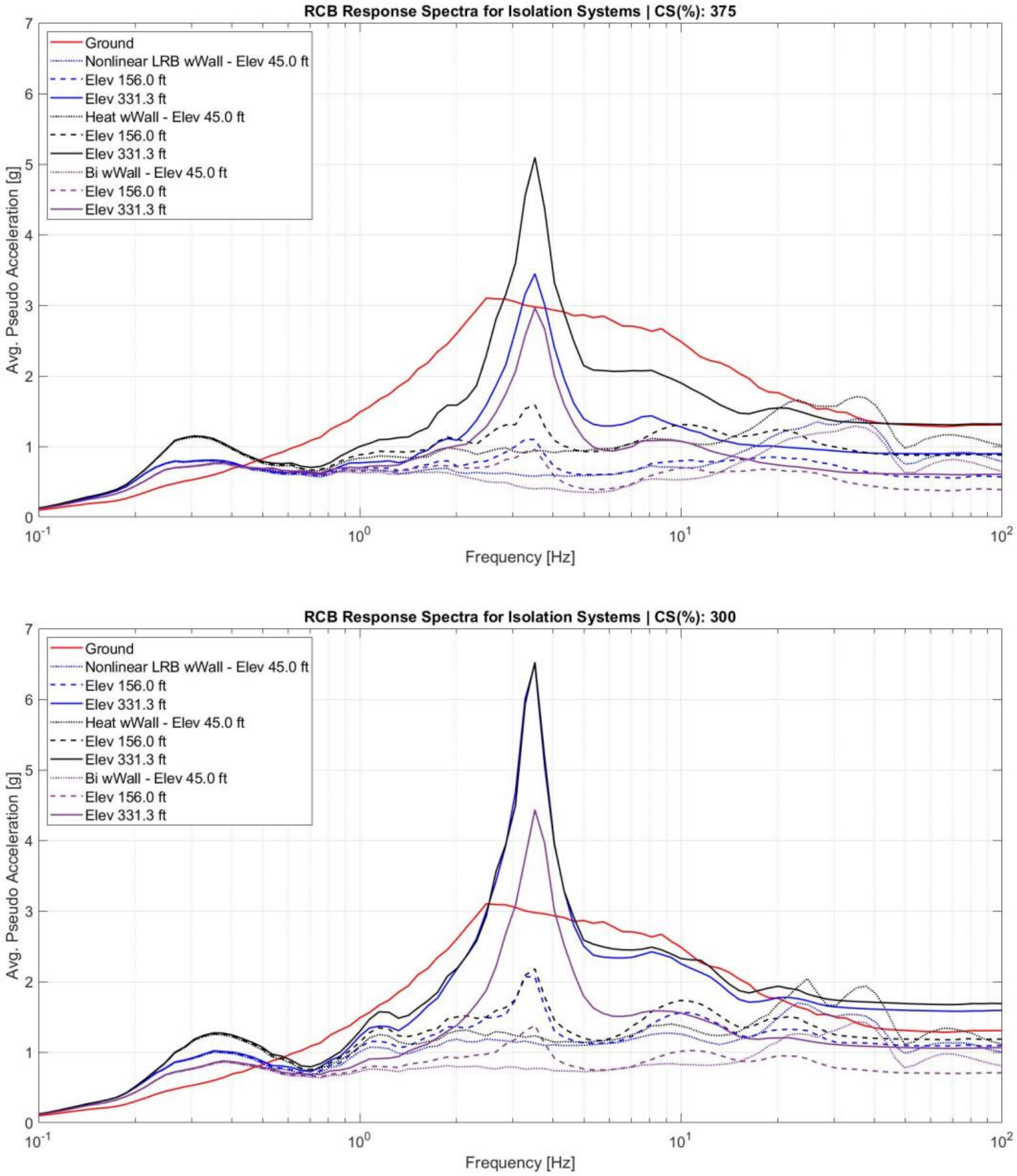
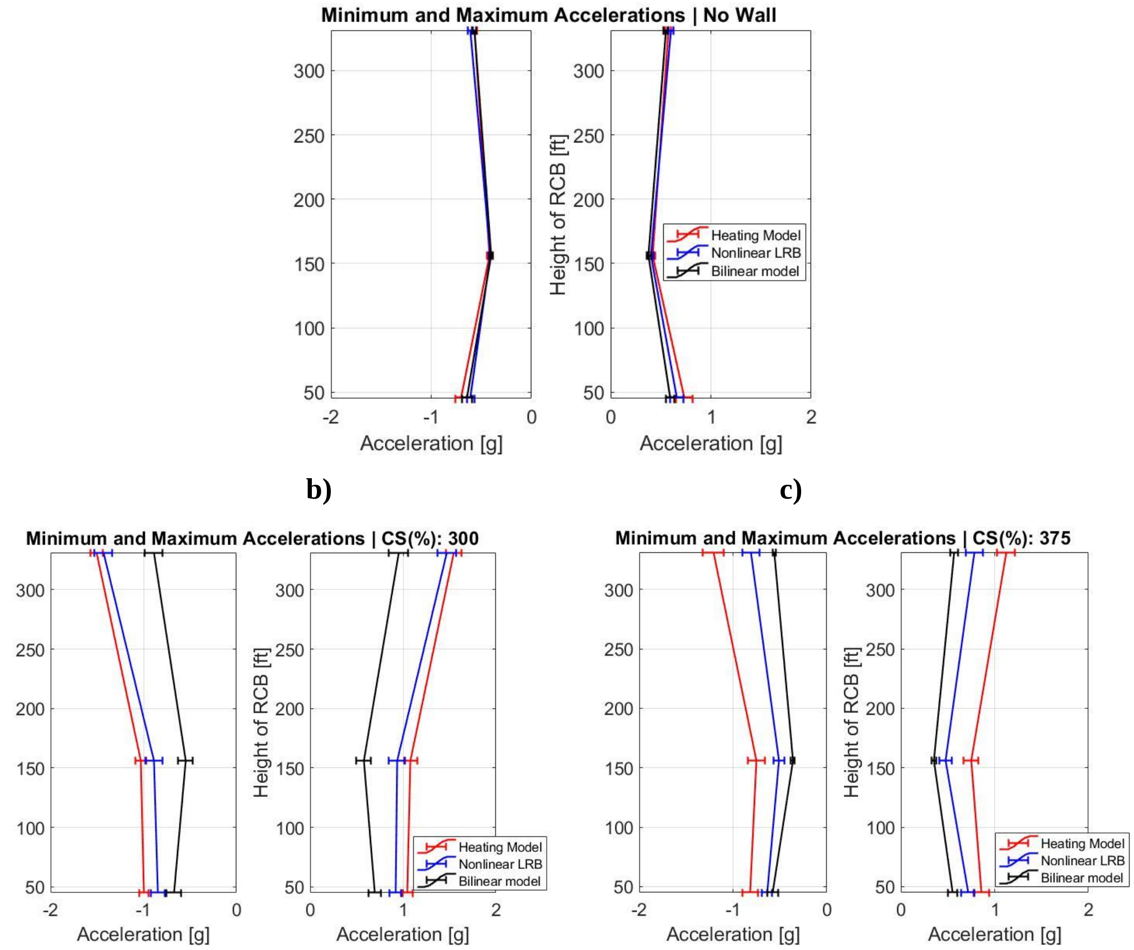


Fig. 3 - Floor response spectra average of 20 GMs moat wall set at | Top: CS 300 % shear strain | Bottom: CS 375% shear strain.

The average minimum and maximum accelerations for the Reactor Containment Building (RCB) are plotted in Fig. 4 and show a similar trend to impact velocities (Fig. 2) and the average floor spectra accelerations (Fig. 3). For the case of no wall, the three different models resulted in very similar accelerations across the three different heights of the RCB. The maximum magnitude of accelerations reaching ~0.75g at the base of the RCB. Observing Fig. 4b, it can be seen that similar to Fig. 2 for CS of 300% shear strain the standard deviation exceeds past the heating model. In Fig. 4b it can be seen that at the height of 331.3ft the Nonlinear LRB model is exceeding that of the hearting model. Fig. 4c, it can be seen that the Nonlinear LRB model is being bounded by both the heating model and the Bilinear model. This shows that the model is dependent on the impact velocity. This can be seen in the average floor response spectra and in the minimum and maximum accelerations. This coincides with previous studies [17] showing that the amplification of the response acceleration at all stories of the building are due to the CS and the impact velocity. Therefore, reducing the velocities before impact may be a key objective to improve the performance of the building considering impact.



a)

b)

c)

Fig. 4 - Minimum and Maximum Accelerations for the Reactor Containment Building (RCB): **a)** No wall | **b)** CS (%): 300 | **c)** CS (%): 375.

5. Conclusions and Future Work

Many state-of-the-art models of Lead Rubber Bearings (LRBs) have been proposed, but a review of existing models with recent experimental data of large-scale bearings showed that these models could not capture all the complexities exhibited, especially under high strains. In this study the introduction of a parallel model was shown to provide good agreement with the experimental data. In order to evaluate the effects of considering Nonlinear LRB model, a heating only model and bilinear model were introduced to compare the response of a structure with these various models. The Nonlinear LRB model overall seemed to be mainly bounded by a heating and bilinear model. Similar to floor response spectra and the impact velocities, the Nonlinear LRB model resulted individual cases exceeding those of the bilinear and the LRX model especially for CS of 300%. This observation was clear when examining the impact velocity, average pseudo floor response spectra, and minimum and maximum accelerations of the RCB. A key finding is that when evaluating the second impact, the Nonlinear LRB resulted in larger reductions than the heating model. The effects of allowing for high strains to develop has not been fully examined.

Future work will extend the modelling for 2D calibration of the LRB experimental data. This may be important to ensure coupling effects are adequately captured for the lead and rubber behavior. The complex bearing behavior may also induce additional torsion in the structure. Finite Element Modeling is also being conducted to understand the behavior of the LRB, especially considering measurements from 2D experimental data.

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