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Variations in the hysteretic behavior of LRBs as a function of applied loading

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Abstract. The study presented herein focused on the change in hysteretic force-deformation behavior of lead rubber bearings (LRBs). The material model used to idealize response of LRBs under cyclic motion is capable of representing the gradual attrition in strength of isolator unit on account of lead core heating. To identify the effect of loading history on the hysteretic response of LRBs, a typical isolator unit is subjected to cyclic motions with different velocity, amplitude and number of cycles. Furthermore, performance of an LRB isolated single degree of freedom system is studied under different seismic input levels. Finally, the significance of lead core heating effect on LRBs is discussed by considering the current design approach for base isolated structures. Results of this study show that the response of an LRB is governed strongly by the amplitude and number of cycles of the motion and the considered seismicity level.

Keywords: lead rubber bearing; isolator tests; quality control tests; seismic isolation; lead core heating

1. Introduction

Among the various types of isolators (i.e., sliding bearings, elastomeric bearings), lead rubber bearings (LRBs) are arguably the most commonly used isolators in protection of structures against the effects of ground motions (Robinson 1982, Tan and Huang 2000). They have been widely used to protect structures against the adverse effects of earthquake ground motions in New Zealand, Japan and the United States (Kelly 1986, Mori *et al*. 1998, Chang *et al.* 2003, Jangid 2010). The lead core of LRB provides a bilinear response through shear deformation with an initial stiffness that is capable enough to resist minor earthquakes and winds (Tyler and Robinson 1984, Mori *et al.* 1998). The bilinear response of LRBs is simulated by a simple generic non-deteriorating hysteretic force-deformation relation in most of the structural analysis programs used in practice. In this generic representation, parameters that control the shape of the hysteresis loop are determined at the start and do not change through the analysis (Mavronicola and Komodromos 2014, Jian *et al.* 2015). There are also more complex methods to idealize the bilinear hysteretic behavior of isolators (Kikuchi and Aiken 1997, Grant *et al.* 2004, Abe *et al.* 2004). Such methods make it possible to simulate the variation in the shape of hysteretic loops instead of using a non-deteriorating representation. Employing more complex models may be appropriate to idealize the displacement-dependent and rate-dependent behavior of bearings. However, since these methods require calibration based on the experimental data, their validity is limited to cases where the employed bearings have similar sizes with the ones tested. Although they are complex in form and require calibration, very few of these models are capable of representing the variation in the shape of hysteresis loop of LRBs due to lead core heating; the most critical cause for the variation of hysteresis loop (Constantinou *et al.* 2007).

The change in shape of hysteretic loops of LRBs under cyclic motion as a function of lead core heating has recently been studied (Kalpakidis and Constantinou 2009a, 2009b) where the authors proposed a mathematical model to idealize the deterioration in strength of LRBs based on instantaneous temperature of the lead core (Kalpakidis and Constantinou 2009a). Proposed methodology is also verified by comparing the analytical responses of LRBs with experiments (Kalpakidis and Constantinou 2009b, Özdemir 2015). The significance of the model has also been demonstrated in terms of maximum isolator displacements. It is demonstrated that using the proposed model may result in more economical design of isolation systems compared to cases in which non-deteriorating representations are used for modeling LRBs (Kalpakidis *et al.* 2010, Özdemir *et al.* 2011, Özdemir and Dicleli 2012). Change in maximum isolator displacements, maximum isolator forces and force-deformation relation of LRBs was also studied by Kalpakidis *et al*. (2010), Özdemir (2014), Özdemir and Bayhan (2015), Ahmadipour and Alam (2017) as a function of lead core heating. Although analyses with recorded ground motions have been performed in these aforementioned studies, the loading patterns (and corresponding change in hysteretic response of LRBs) used in testing protocols of isolators have not been addressed. It is to be noted that the characteristics of any isolator used in the design of seismic isolated structures, are established in

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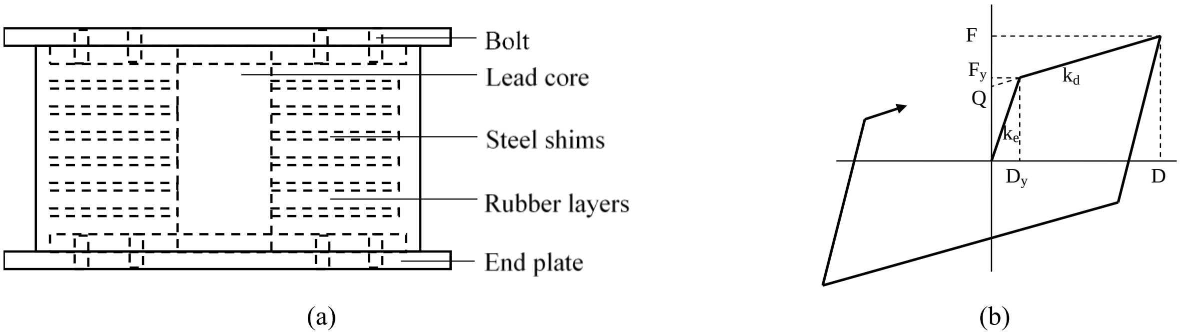


Fig. 1(a) Composition of LRB isolators, (b) idealized force-deformation relation of LRBs

accordance with the test results conducted under specific loading conditions. It is also noteworthy that only as-recorded ground motions were used in the previous studies and the effect of scaling is discarded. However, in order to fulfill the code requirements during nonlinear response history analysis, ground motions are generally scaled to get compatible with a design spectrum. Thus, there is a need to identify the change in force-deformation relation of LRBs subjected to different loading conditions (amplitude and velocity of loading, and number of cycles in the loading sequence) and ground motions with different scale factors (representative of different seismic input levels).

This study presents the variation in hysteretic behavior of an LRB as a function of lead core temperature, due to differing loading protocols applied in the tests performed to determine design characteristics of LRBs. To achieve this purpose, the deteriorating bilinear hysteretic behavior of LRBs, which is a function of the lead core temperature, is used to present the results of a parametric research in which the rise in temperature of lead core is studied as a function of the loading. The selected parameters are velocity and amplitude of loading, and number of cycles in the loading. Then, the considered LRB is subjected to earthquake motions representative of different input levels. In pursuit of the objective, an isolated single degree of freedom system is subjected to a ground motion record with different scale factors that represent variable seismicity levels. Finally, variation in the hysteretic behavior of LRBs is investigated from the design point of view by performing a bounding analysis.

2. Non-deteriorating idealization of LRBs

LRBs are composed of alternate layers of steel and rubber with a central hole through which a lead plug is inserted (Fig. 1(a)). In most of the structural analysis tools where nonlinear response history analyses option is available, the hysteretic behavior of LRBs is generally represented by a stable bilinear force-deformation relationship as shown in Fig. 1(b). Here, Q is the characteristic strength, k_d is the post-yield stiffness, and k_e is the initial elastic stiffness. F_y and D_y are the yield force and yield displacement, respectively. The characteristic strength, Q, is the force intercept at zero displacement and it is calculated by Eq. (1).

$$Q = \sigma_{YL} \cdot A_L \tag{1}$$

In Eq. (1), σ_{YL} is the average yield stress of the lead core which is generally calculated by taking the average of effective yield stress of lead in three cycles of harmonic motion at large amplitude consistent with the expected seismic demand and A_L is the cross-sectional area of the lead core. Yield force, F_y, which is needed for constructing the bilinear hysteretic representation of LRBs, is obtained by Eq. (2). The relation of post-yield stiffness, k_d, and isolation period T_d is given in Eq. (3) where W is the weight acting on the isolator and g is the gravitational acceleration constant.

$$F_y = Q + k_d \cdot D_y \tag{2}$$

$$T_d = 2\pi \sqrt{\frac{W}{k_d g}} \tag{3}$$

Eqs. (1) and (2) state that the strength of an LRB is directly related to the yield stress, σ_{YL}, of the lead core. Thus, in order to reduce the strength of the bearing with the initiation of deformation, σ_{YL} should be reduced accordingly. The mathematical model proposed by Kalpakidis and Constantinou (2009a) provides a methodology to reduce the initial yield stress of lead core by defining σ_{YL} as a function of lead core temperature, T_L. Details of this approach are discussed in the following section.

3. Formulation of lead core heating effect

Experimental studies conducted with LRBs have shown that LRBs subjected to cyclic motion experience a gradual reduction in strength, resulting in a deteriorating bilinear hysteretic force-deformation relation (Robinson 1982). Fig. 2 presents hysteretic loops of a typical LRB subjected to cyclic motion. It is demonstrated in Fig. 2 that the initial strength of the bearing reduces with the initiation of motion. In order to idealize such variation in hysteretic behavior of LRBs, Kalpakidis and Constantinou (2009a) proposed a mathematical model that accounts for the variation in the characteristic strength (or yield stress of lead) of LRBs due to the instantaneous temperature of the lead core. The

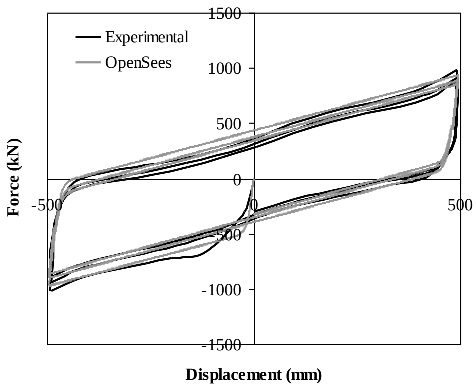


Fig. 2 Deteriorating hysteretic behavior of a typical LRB (adopted from Özdemir 2015)

proposed model enables the determination of instantaneous lead core temperature and updates the yield stress of the lead at each time instant as a function of the calculated lead core temperature. The updated yield stress of lead is then used to determine the instantaneous strength of the bearing. Thus, this model makes it possible to consider a deteriorating hysteretic force-deformation relation for LRBs rather than a generic steady-state one. The validity of the deteriorating model used in representing the hysteretic behavior of LRBs is also tested in Fig. 2 where black solid line represents the experimental behavior of the LRB employed in this study (see Section 4 for geometrical features) whereas grey solid line represents the analytical response of the same bearing. It is seen that the deteriorating material model is highly accurate in simulating the actual behavior of LRBs without need for any calibration.

According to the model proposed by Kalpakidis and Constantinou (2009a), the rate of the temperature rise in the lead core due to cyclic motion of LRBs, $\dot{T}_L$, is calculated by the following set of equations

$$\dot{T}_L = \frac{\sigma_{YL}(T_L)\cdot\left|Z\cdot\dot{U}\right|}{\rho_L\cdot c_L\cdot h_L} - \frac{k_s\cdot T_L}{a\cdot\rho_L\cdot c_L\cdot h_L}\cdot\left(\frac{1}{F}+1.274\cdot\left(\frac{t_s}{a}\right)\cdot\left(t^+\right)^{-1/3}\right) \tag{4}$$

$$F = \begin{cases} 2\cdot\left(\frac{t^+}{\pi}\right)^{1/2} - \frac{t^+}{\pi}\cdot\left[2-\left(\frac{t^+}{4}\right)-\left(\frac{t^+}{4}\right)^2-\frac{15}{4}\cdot\left(\frac{t^+}{4}\right)^3\right], & t^+ < 0.6 \\ \frac{8}{3\cdot\pi} - \frac{1}{2\cdot\left(\pi\cdot t^+\right)^{1/2}}\cdot\left[1-\frac{1}{3\cdot\left(4\cdot t^+\right)}+\frac{1}{6\cdot\left(4\cdot t^+\right)^2}-\frac{1}{12\cdot\left(4\cdot t^+\right)^3}\right], & t^+ \geq 0.6 \end{cases} \tag{5}$$

$$t^+ = \frac{\alpha_s\cdot t}{a^2} \tag{6}$$

$$\sigma_{YL}\left(T_L\right) = \sigma_{YL0}\cdot exp\left(-E_2\cdot T_L\right) \tag{7}$$

In the above equations, h_L is the height of lead, a is the radius of lead, t_s is the total steel plate thickness, ρ_L is the density of lead, c_L is the specific heat of lead, α_s is the thermal diffusivity of steel, k_s is the thermal conductivity of steel, σ_{YL0} is the yield stress of lead at the reference (initial) temperature, t^+ is the dimensionless time, t is the time since beginning of motion, and E_2 is the constant that relates the temperature and yield stress. Except for the geometric parameters (h_L, a, and t_s), the rest of the parameters are based on the material properties. These properties are given by Kalpakidis and Constantinou (2009a) as follows: ρ_L=11200 kg/m^3, c_L=130J/(kg°C), k_s=50W/(m°C), α_s=1.41×10^{-5} m^2/s, E_2=0.0069/°C. The instantaneous temperature in the lead core calculated through Eqs. (4)-(7) is then used to find the lateral force, F_b, carried by LRB as;

$$F_b = k_d\cdot U + \sigma_{YL}\left(T_L\right)\cdot A_L\cdot Z \tag{8}$$

where $\sigma_{YL}(T_L)$ is the yield stress of lead based on the instantaneous temperature of the lead core, and Z is the hysteretic dimensionless quantity that satisfies the first-order differential equation given below;

$$D_y\cdot\dot{Z} = \left(A-\left|Z\right|^2 B\cdot\left(1+sgn\left(\dot{U}\cdot Z\right)\right)\right)\cdot\dot{U} \tag{9}$$

where A and B are dimensionless quantities that control the shape and size of the hysteresis loop of the bearings, and $\dot{U}$ is the relative velocity of the bearing. In Eq. (9), A and B should satisfy the relation of $A = 2B$ (Mokha *et al.* 1993). In the present study, A and B are chosen as 1 and 0.5, respectively. This assumption is essential because it assures that the force and displacement vectors will be in the same direction.

4. Lead core heating effects due to variations in loading

In this section, three sets of analyses are performed with the verified hysteretic behavior of the LRB used by Özdemir (2015). The LRB has a diameter of 950 mm with a lead core diameter of 254 mm. It consists of 29 layers of rubber and 28 layers of steel with thicknesses of 7 mm and 3 mm, respectively. The total height, h_L, of the LRB is 287 mm with a total steel plate thickness, t_s, of 84 mm. The analytically verified hysteretic behavior of the LRB specimen (Özdemir 2015) was obtained from three fully reversed cycles of loading at the maximum displacement with an axial load of 5879 kN. The amplitude of the maximum displacement and the loading rate employed during the testing of the considered LRB are 495 mm and 20.8 mm/s, respectively. Since the analytical simulation in OpenSees is quite satisfactory to represent the actual hysteretic behavior of the LRB obtained from the test results, the same hysteretic representation is used in the parametric analyses. It should be noted that Kalpakidis and Constantinou (2009) stated that the proposed formulations for predicting the lead core temperature and corresponding deterioration in strength of LRB do not require any calibration using the data obtained from tests of bearings. Apart from the existing hysteretic models based on phenomenological constructions, there is no restriction regarding the size of the bearing for the use of formulations proposed by Kalpakidis and Constantinou (2009).

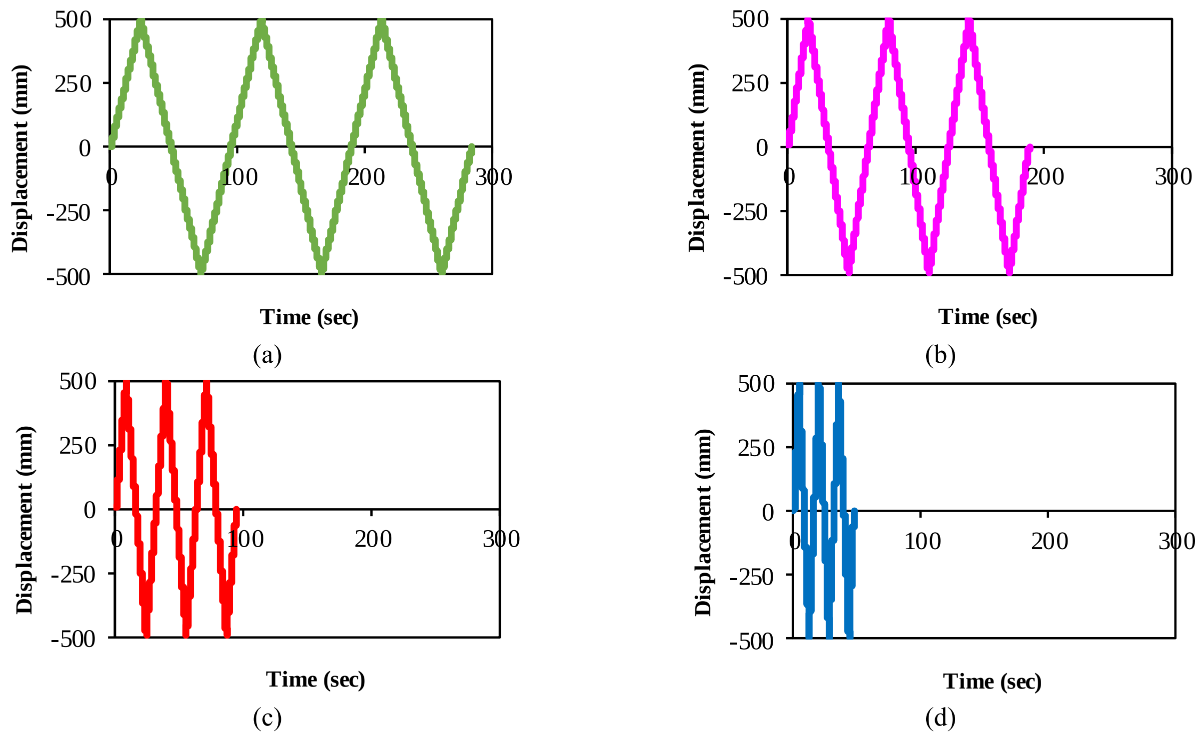


Fig. 3 Applied loading histories for velocities of (a) 20.8 mm/s (b) 31.2 mm/s (c) 62.4 mm/s (d) 124.8 mm/s

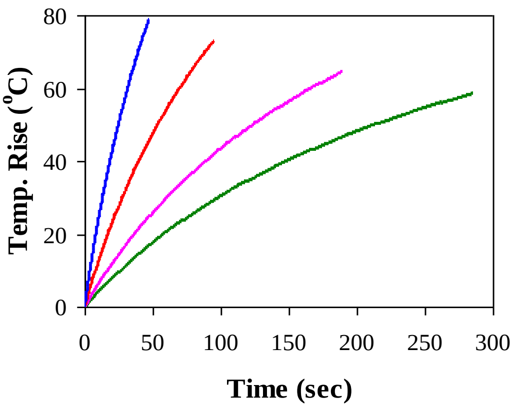


Fig. 4 Analytically obtained temperature rises in lead core for loading velocities of 20.8 mm/s (green line), 31.2 mm/s (pink line), 62.4 mm/s (red line), 124.8 mm/s (blue line)

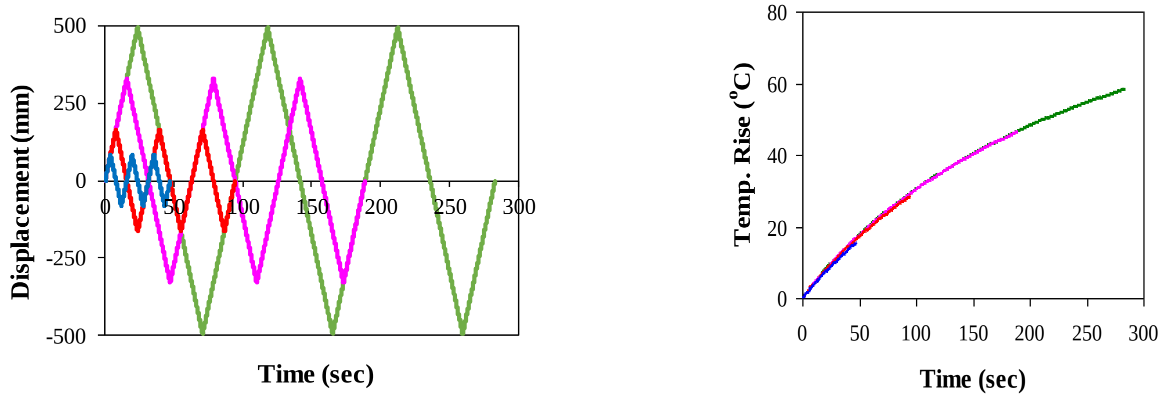
In the following sections, the LRB specimen under examination is subjected to different loading patterns to identify the effects of i) velocity; ii) amplitude and iii) number of cycles in the loading on heating of the lead core. Thus, the comparative analyses of the LRB under different loading patterns are presented in terms of the rise in the lead core temperature.

4.1 Effect of loading velocity

In order to determine the effect of loading velocity on lead core heating, the considered LRB is subjected to four distinct loading patterns as shown in Fig. 3. The loading pattern given in Fig. 3(a) is the one known to be used to obtain experimental data presented in Fig. 2 and was used in verification of the material model by Özdemir (2015) where loading velocity was 20.8 mm/s, loading amplitude 495 mm, and number of cycles 3. In the interest of determining the effect of loading velocity, the amplitude of the loading (495 mm) and the number of cycle (3) are kept constant while it is the loading velocity that varies.

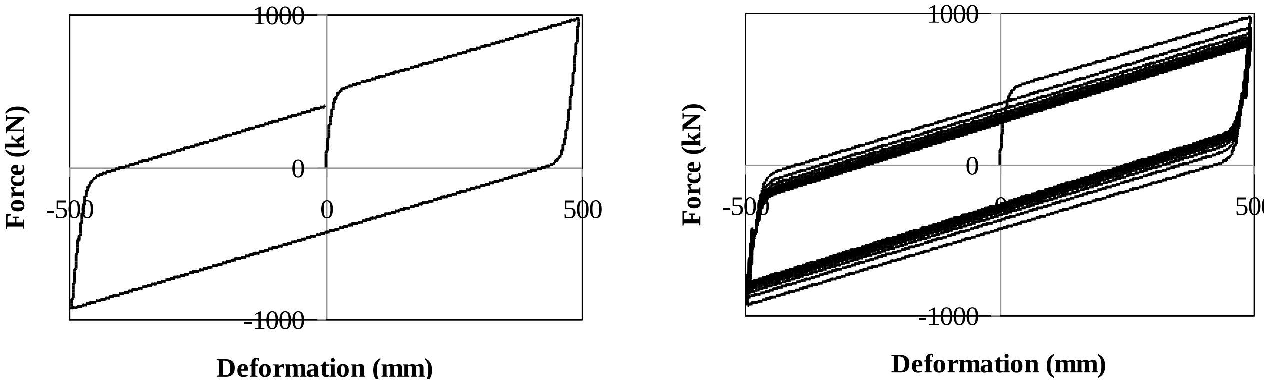
The loading histories represented by Figs. 3(b)-(d) have velocities of 31.2 mm/s, 62.4 mm/s, and 124.8 mm/s (multiples 1.5, 3.0, and 6.0 of the original loading rate 20.8 mm/s applied in the test), respectively. The corresponding temperature rises in the lead core are displayed in Fig. 4.

Colors of the solid lines in Fig. 4 are used to represent the loading patterns given in Fig. 3. Fig. 4 reveals that the lead core temperature rise is controlled by variation in loading velocity. As the loading velocity increases, the lead core temperature increases. For instance, the maximum amount of rise in the lead core temperature is 58.5°C when the loading velocity is 20.8 mm/s. On the other hand, it is 78.9°C when the loading velocity is 124.8 mm/s. As a result, the reductions in the initial strength of the considered LRB are in the order of 33 percent and 42 percent, respectively. The corresponding total dissipated energies (defined as the area under the force-deformation curves) when loading velocities are 20.8 mm/s, 31.4 mm/s, 62.4 mm/s and 124.8 mm/s are 2202 kN.m, 2164 kN.m, 2114 kN.m and 2074 kN.m, respectively. The reduction in total energy dissipation capacity is about 6% when loading velocity increases from 20.8 mm/s to 124.8 mm/s. Thus, slight changes in loading rate will result in negligible variation in hysteretic behavior of LRB. The characterization tests of the bearings are typically performed at a velocity of 25 mm/s.



(a) (b)

Fig. 5(a) Applied loading histories for amplitudes of 495 mm (green line), 330 mm (pink line), 165 mm (red line), 82.5 mm (blue line) (b) corresponding lead core temperatures



(a) (b)

Fig. 6 Force-deformation curves for (a) 1 cycle of loading (b) 10 cycles of loading

4.2 Effect of loading amplitude

To investigate the effect of loading amplitude on the performance of LRBs in terms of lead core temperature, the considered LRB (see Fig. 2 for the corresponding force-deformation relation) is subjected next to cyclic motions with different amplitudes when velocity of the loading (20.8 mm/s) and number of cycles (3) are kept constant. Employed loading patterns are presented in Fig. 5(a) where the green line represents the displacement history subjected to LRB during the experiment.

The selected amplitudes of loadings are 495 mm, 330 mm, 165 mm, and 82.5 mm. The corresponding rises in lead core temperatures obtained from the analysis program OpenSees (2009) are given in Fig. 5b. Each line in Fig. 5(b) is represented by the same color used to identify the loading pattern given in Fig. 5(a). Computed temperature rises in the lead core of analyzed LRB are 58.5°C, 46.4°C, 28.4°C, and 15.4°C, respectively. The corresponding reductions in the initial strength of the LRB are 33, 27, 18, and 10 percent, respectively. Thus, the increase in temperature of lead core depends on the amplitude of loading and the effect of lead core temperature at low amplitude motions can be neglected. This observation is important because response of an LRB subjected to low-, medium-, or high-seismicity levels may be different due to variation in the hysteretic behavior of the bearing.

4.3 Effect of number of cycles of loading

Next, variation in the response of the considered LRB will be examined as a function of the number of cycles in the loading in terms of lead core temperature. For this purpose, the LRB is subjected to loadings with increasing number of cycles namely, 1, 3, 5 and 10, while the amplitude (495 mm) and the velocity (20.8 mm/s) of loading are kept constant. The corresponding temperature increases in the lead core are computed as 29.3°C, 58.5°C, 73.5°C and 90.6°C, respectively. Not surprisingly the rise in lead core temperature increases with increasing number of cycle. To illustrate the change in hysteretic loops of the considered LRB due to increasing number of cycles, Fig. 6 is drawn. In Fig. 6(a) and 6(b), hysteretic loops of LRB obtained from analyses under 1 and 10 cycles of motions are given, respectively. The total energy dissipated in the first cycle is 829 kN.m whereas it is equal to 520 kN.m in the tenth cycle. The corresponding effective damping ratios and effective stiffness values at 1st and 10th cycles are 0.28 and 0.21, and 1968 kN/m and 1593 kN/m per ASCE-7 (2010). This reveals that the reductions in the initial

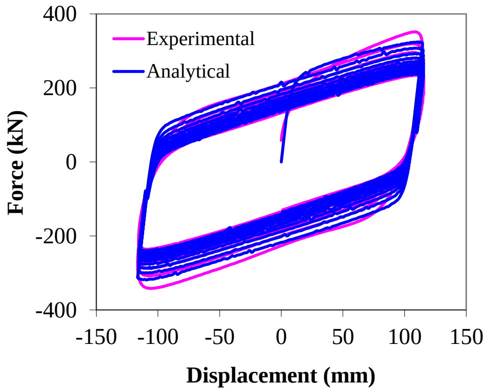


Fig. 7 Comparison of analytically predicted (OpenSees) and experimentally obtained hysteretic behavior of a typical LRB (experimental data is adopted from Kalpakidis *et al.* 2010)

Table 1 Variation in effective damping ratio and effective stiffness values

Loading Amplitude	200 mm	300 mm	400 mm	495 mm
β_{eff1}	0.39	0.35	0.30	0.28
β_{eff10}	0.35	0.29	0.24	0.21
Reduction, percent	10	17	20	25
k_{eff1} (kN/m)	3406	2601	2201	1968
k_{eff10} (kN/m)	2635	2026	1746	1593
Reduction, percent	23	22	21	19

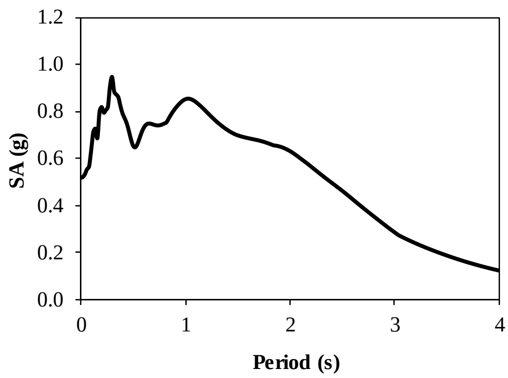


Fig. 8 Acceleration spectrum of Erzincan record for 5% damping

effective damping ratio and initial effective stiffness are 25- and 19 percent at the 10th cycle, respectively. However, according to ASCE-7 (2010), the reduction in both initial effective damping ratio and initial effective stiffness shall not be greater than 20 percent at any cycles of loading. It is seen that the hysteretic behavior of the LRB under applied loading does not satisfy these requirements.

We note that the given reductions above in both initial effective damping ratio and initial stiffness ratio at the 10th cycle depends on the amplitude of the loading. At this point, further loading amplitudes are considered as 200 mm, 300 mm, and 400 mm while the loading rate and number of cycles are 20.8 mm/s and 10, respectively. Such an investigation will identify whether ASCE-7 (2010) requirement can be satisfied at any level of isolator displacement.

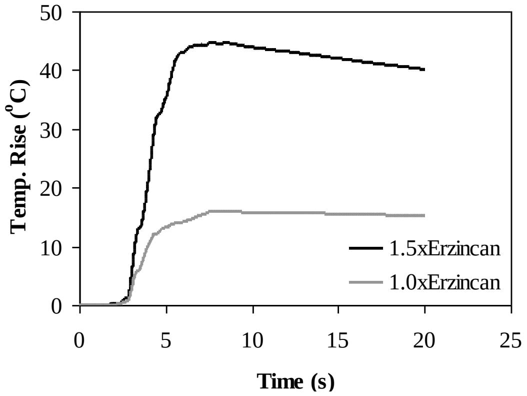


Fig. 9 Analytically obtained temperature rises in lead core for different seismicity level

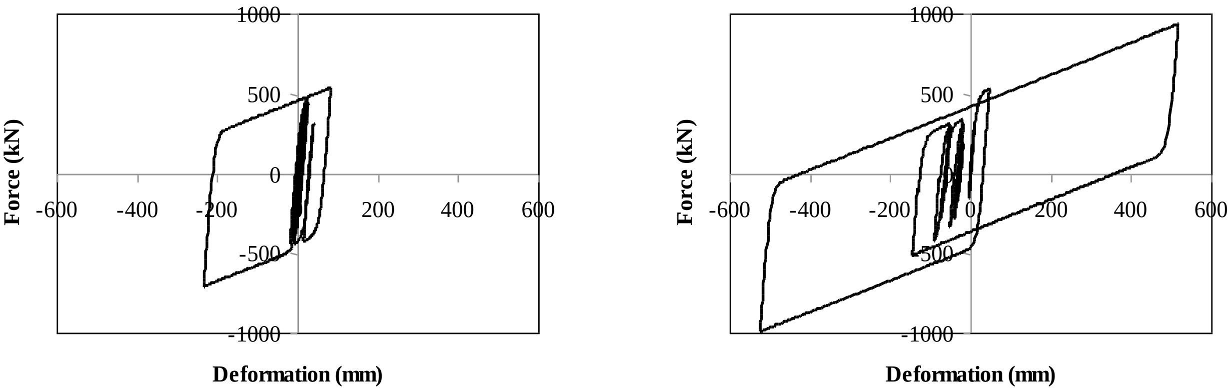
Results are tabulated in Table 1 where β_{eff1} and β_{eff10} represent the effective damping ratios at the 1st and 10th cycles, k_{eff1} and k_{eff10} stand for the effective stiffness values at the 1st and 10th cycles, respectively. Table 1 clearly indicates that almost none of the loadings considered here satisfies the requirements when the change in effective stiffness value is of concern. However, when the change in effective damping ratio is of interest, applied loading cycles will result in hysteretic behavior that satisfy ASCE-7 (2010) requirements with the exception of loading with maximum amplitude.

In the above discussion, although the results based on analytical representations indicate that the code requirement, which is the reduction in both initial effective damping ratio and initial effective stiffness shall not be greater than 20 percent at any cycles of loading, is not satisfied, such a conclusion must rely on carefully conducted test results rather than analytical experiments. Thus, there is a need to ensure that the deteriorating model used in the analytical representation is also valid under large number of cycles, specifically, 10 cycles as in the above discussion. For this purpose, hysteretic behavior of an LRB (h_L=224 mm, a=70 mm, t_s=71 mm), obtained from a test conducted under 10 cycles of displacement history (the amplitude of the motion is 115 mm) is used to verify the validity of the employed analytical model also in case of large number of cycles.

Fig. 7 presents force-deformation relations of the considered LRB for both experimental and analytical cases. It is seen that the analytical model for LRB behavior is also very accurate even under loadings with large number of cycles. As a result, the analytical results presented in Table 1 are admissible in deriving the corresponding conclusions.

5. Performance of LRBs under varying seismicity levels

In this section, two sets of analyses are performed to investigate the performance of LRB isolated structures subjected to different levels of seismicity. For this purpose, horizontal north-south component of the 1992 Erzincan



(a) (b)

Fig. 10 Force-deformation curves for (a) 1.0×Erzincan record (b) 1.5×Erzincan record

record (M_w=6.7, R=4.4 km, soil classification per USGS = C, PGA=0.52 g, PGV=83.9 cm/s, PGD=27.4 cm) is applied to an idealized isolated single degree of freedom system with different scale factors in order to represent different seismicity levels.

The weight acting on the LRB is selected so that the isolation period (based on post-yield stiffness) is equal to 3.0 s which is the case for a hospital building in Turkey and equals 2345 kN. The selected record is scaled-up and then used to simulate different ground motion levels. Hence, this record is multiplied by 1.5 and 1.0 to represent the maximum considered earthquake (MCE) and design-based earthquake (DBE) levels, respectively in accordance with Turkish Earthquake Code (TEC 2007). Figure 8 presents the 5 percent damped acceleration spectrum of Erzincan record.

The computed temperature rises in lead core of the two systems versus time are depicted in Fig. 9 whereas corresponding force-deformation curves are given in Fig. 10 for both of the seismicity levels.

In Fig. 9, the black solid line represents the high-seismicity (representative of MCE) level (the original Erzincan record is scaled-up by a factor of 1.5) whereas the grey solid line represents the medium-seismicity (representative of DBE) level (the original Erzincan record). There is a significant rise in the lead core temperature when a scale factor of 1.5 is used. The observed lead core temperature is about 45°C which is 3 times that of the analysis conducted for the unscaled record. The corresponding maximum isolator displacements when scale factors are 1.0 and 1.5 are 234 mm and 524 mm, respectively. Thus, the amplification in isolator displacement when scale factor is 1.5 is 2.24 times that for the original record. When 1.5 times the original record is used as input (Fig. 10(b)), the deterioration in the hysteretic response is observed clearly. Another inference from Figs. 9 and 10 is that the value of scale factor is of crucial importance in the response of LRB isolated structures. Although studies exist indicating that a scale factor can be up to 10 (Hancock *et al.* 2008), it is seen that temperature dependent behavior of LRBs is highly sensitive to this scale factor. Thus, further research should be focused on this issue.

6. Significance of lead core heating effects from design point of view

In most cases, engineers must perform nonlinear response history analyses (NRHA) to check the validity of the maximum isolator displacements calculated in the preliminary design stage. The code requirement for conducting NRHA is to use ground motions compatible with the design response spectrum. This is usually achieved by scaling up the recorded original ground motions. However, it is known that scaling up the original records will result in higher isolator displacements compared to the cases where original records are used in the analyses. Increased amplitude will result in higher lead core temperature and further reduction in the initial strength of the LRB denoted in previous sections. The gradual reduction in strength of the bearing as a function of lead core temperature also results in variation of energy dissipation capacity of the bearing at each cycle of the motion. Current design applications for seismic isolated structures are not capable of accounting for such variation. Instead, two non-deteriorating force-deformation idealizations for a single isolator, considering lower- and upper-bound properties, are employed in the design phase to mimic the variation in the hysteretic behavior. Lower-bound properties are generally used to estimate the maximum isolator displacements and determined by taking the average value of the effective yield stress of lead in the first three cycles. Further, upper-bound properties are generally used to estimate the maximum isolator force and defined as the effective yield stress at the first cycle of the bilinear hysteretic response. To evaluate the efficiency of performing bounding analyses in performance estimation of LRB isolated structures when ground motions are scaled up according to code requirements, the idealized isolated model defined in the previous section is also considered here. In this sense, the hysteretic behavior of LRB obtained from bounding analyses are compared with the ones when lead core heating effect is included. Comparisons are

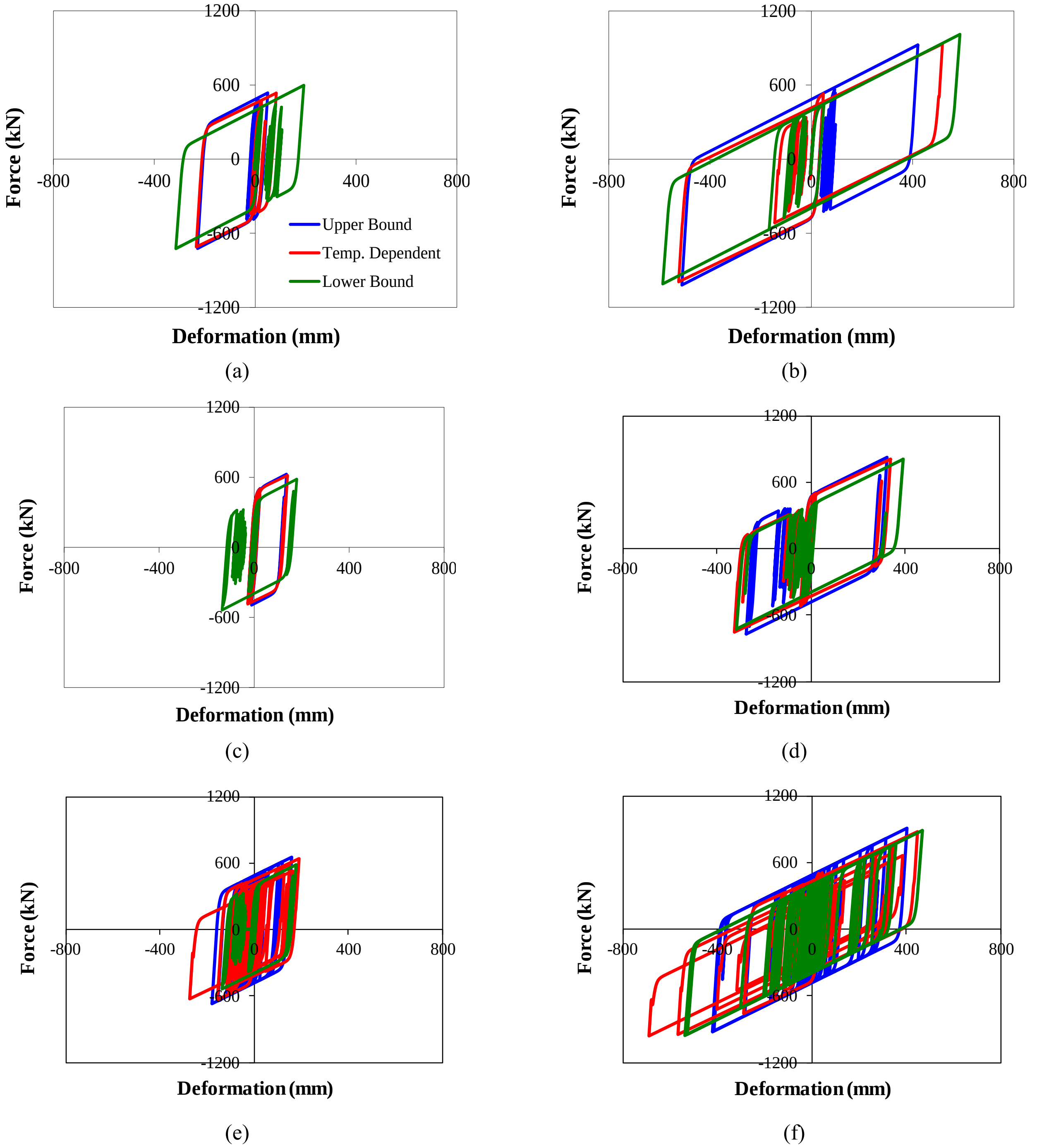


Fig. 11 Comparison of force-deformation curves obtained from both bounding analysis and lead core heating included cases for (a) 1.0×Erzincan record (b) 1.5×Erzincan record (c) 1.0×Imp.Val. record (d) 1.5×Imp.Val. record (e) 1.0×Chi-Chi record (f) 1.5×Chi-Chi record

conducted by means of force-deformation curves of LRB obtained from NRHA in which both the original and scaled ground motion records were used.

Effective yield stresses of lead used to construct bilinear hysteretic representations for lower- and upper-bound conditions are determined as 7.8 MPa and 9.55 MPa from Fig. 2, respectively. Then, idealized seismically isolated system is subjected to excitations of 1.0 (representative DBE) and 1.5 (representative of MCE) times the selected records. To avoid having results specific to Erzincan record used in the previous section, two randomly selected additional ground motion records are also employed in the analyses: Array #5 (230 component) of Imperial Valley (M_w=6.5, R=4 km, soil classification=C (per USGS), PGA=0.38 g, PGV=90.5 cm/s, PGD=63 cm) and TCU065 (W component) of Chi-Chi (M_w= 7.6, R=0.6 km, soil classification=C (per USGS), PGA=0.81 g, PGV=126.2 cm/s, PGD=92.6 cm). Force-deformation loops obtained from NRHA are presented in Fig. 11.

In order to quantify the amount of amplification in maximum isolator displacement due to scaling of ground motion records, the peak displacements obtained from lower-bound and temperature dependent analyses are compared. The maximum isolator displacements obtained from lower-bound analyses using Erzincan record are 314 mm and 587 mm for scale factors 1.0 and 1.5, respectively whereas they are 233 mm and 524 mm for temperature dependent analyses. Amounts of amplification in maximum isolator displacements are 187% and 224% for lower-bound and temperature dependent analyses, respectively. The same comparison results in the following ratios: 218% and 240% for Imperial Valley record, 299% and 252% for Chi-Chi record, respectively. It is interesting to observe that temperature dependent analyses of Erzincan and Imperial Valley records are more prone to change in scale factor in terms of amplification in maximum isolator displacements. On the contrary, for Chi-Chi record, amplification in maximum isolator displacement of lower-bound analysis is larger than that of the temperature dependent analysis. As shown in Fig. 11, number of cycles that LRB undergoes in case of Chi-Chi is larger than those of Erzincan and Imperial Valley records. Since the temperature dependent behavior of LRB is functions of both amplitude of motion and number of cycle, scaling up records having similar characteristics (large number of cycles) with Chi-Chi will result in higher temperature rise in the lead core of LRB. As a result, bounding analysis may not provide a safe estimation for maximum isolator displacement as shown in Fig. 11(f).

The purpose of bounding analysis is to provide an envelope for both isolator displacements and isolator forces with reasonable overestimation. However, Fig. 11 demonstrates that there may be cases where bounding analysis is not capable of providing overestimated maximum isolator displacements consistently. Hysteretic response of the LRB subjected to TCU065 record shows that the maximum isolator displacement for lower bound analysis is less than that of temperature dependent response even when the unscaled ground motion is of concern (Figs. 11(e) and 11(f)). Moreover, it is also interesting to observe that the amount of overestimation in maximum isolator displacements provided by bounding analysis is a function of the scale factor applied to the motion. In the analyses where the original Erzincan record is used, the amount of overestimation in isolator displacement is almost 35 percent but it is equal to 12 percent when 1.5 times the original record is employed. The similar comparison for Imperial Valley record result in 27 percent and 16 percent overestimations in maximum isolator displacements for scale factors of 1.0 and 1.5, respectively. For the analyses where Chi-Chi record was used, bounding analyses turns out to be unsafe in terms of maximum isolator displacements. These results indicate that performing bounding analyses for LRBs may not be safe in terms of maximum isolator displacements and needs to be complemented with the calculated response for temperature dependent behavior of LRBs.

7. Conclusions

In this paper, a recently proposed mathematical model, that takes into account the gradual reduction in strength of LRBs as a function of the lead core temperature, is used to present the results of a parametric research where the rise in temperature of lead core and the corresponding change in hysteretic behavior of LRBs are examined as a function of the loading. Selected parameters to represent different loading conditions are the following: velocity and severity of the loading, and number of cycles in the loading. Thus, several displacement histories were applied to the LRB model. Then, performance of LRBs subjected to different levels of seismicity is studied. For this purpose, an idealized isolated single degree of freedom system having identical isolation properties with that of a hospital building in Turkey is studied. Different levels of seismic input are represented by considering the scale factors of 1.0 and 1.5 for the considered ground motion record. Finally, the idealized seismic isolated system is analyzed for ground motions with different characteristics to test the efficiency of bounding analysis in determining the maximum isolator displacements. Results of this study support the following conclusions:

• Given that the typical value for loading rate used in the characterization tests of LRBs is 25 mm/s, it appears that employing even 5 times faster loading rates (125 mm/s) will result in negligible change in hysteretic energy dissipation capacity of the LRB. When loading rate is increased from 20.8 mm/s to 124.8 mm/s, reduction in total dissipated energy in three cycles of 495 mm loading is less than 6 percent.

• The amounts of increments in the lead core temperatures obtained from the analyses conducted with a loading rate of 20.8 mm/s and 3 cycles of different amplitudes ranging from 495 mm to 82.5 mm fall between 54°C and 15.4°C. The corresponding reductions in the initial strengths due to such temperature increases are 33 and 10 percent, respectively. This indicates that the effect of lead core heating can be neglected when the loading amplitudes are low.

• The LRBs subjected to different numbers of loading cycles show that there will be significant change in the hysteretic behavior of LRBs with increasing number of cycles. For addressing this concern, code provisions imply that reduction in both the effective damping ratio and effective stiffness of LRB obtained from any loading cycle shall not be less than 20 percent. However, the analyses results obtained from the different levels of loading amplitudes show that the reductions may be in the order of 25 percent for both effective damping ratio and effective stiffness. Based on the limited results presented here, the 20 percent code limitation appears to be questionable.

• Scaling of ground motion records is found to be an important parameter that should be considered with caution when they are used in the nonlinear response history analyses of LRB isolated structures. Using high scale factors for ground motion records to match a response spectrum may result in misleading results due to probable high lead core temperature and also severe reductions in the initial strength of LRB.

• Analysis results show that the level of overestimation in maximum isolator displacements depends on the amplitude of the scale factor. This is due to increased level of reduction in strength of isolator in analyses with high scale factor. It is found that, there may be cases where bounding analysis may not fulfill its intended purpose to provide an envelope for maximum isolator displacements of LRBs. Thus, the bounding analysis should be complemented with analyses where lead core heating effect is considered.

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