Significance of loading history on the hysteretic behaviour of isolators

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Abstract The study presented herein focused on the hysteretic force-deformation behavior of lead rubber bearings by considering a deteriorating hysteretic material model. The material model is capable of representing the gradual reduction in lateral strength of an LRB as a function of instantaneous lead core temperature. The deteriorating material model is used to perform a parametric research to identify the effects of velocity and amplitude of loading. Under the effect of different loading histories, the amount of increment in lead core temperature and change in hysteretic response of isolator was studied. Results of this study showed that the hysteretic behavior of an LRB obtained from displacement controlled tests is sensitive to both the velocity and the amplitude of the motion.

1 Introduction

In the nonlinear analyses of lead rubber bearing (LRB) isolated structures, the hysteretic behavior of LRBs is generally idealized by means of non-deteriorating representations where the upper and lower bound properties of the isolator are used in bounding analyses. In such analyses, parameters that control the shape of hysteresis loops are determined at once and do not change through the analysis. Although this modeling is not appropriate to mimic the real hysteretic behavior of LRBs, the lack of ability to model the deteriorating force-deformation relation is the main reason for such a modeling approach. However, recently a mathematical model has been proposed by Kalpakidis and Constantinou \cite{1} that is capable of modifying the strength of LRB during the exerted cyclic motion. That model enables the computation of temperature rise in the lead core under the applied loading and update the strength of LRB instantaneously as a function of that temperature rise. Proposed methodology is verified by comparing the analytical responses of LRBs with those of experimental ones \cite{2}.

Since the model proposed to idealize the deteriorating hysteretic behavior of LRBs is rather new, there are only a few research in the literature that consider the
reduction in lateral strength of LRBs due to lead core heating [3-8]. In these limited number of studies, several nonlinear dynamic analyses have been conducted under both uni-and bi-directional earthquake excitations. The corresponding results were used to quantify the amount of variation in isolator displacements and/or hysteretic response of isolator units in comparison to response obtained from bounding analyses. Outcomes of the above mentioned studies revealed the significance of employing deteriorating hysteretic behavior of LRBs in establishing the response of an LRB isolated structure. However, none of these studies address the effect of different loading histories and corresponding change in hysteretic response of LRBs used in testing protocols of isolators. On the other hand, it is to be noted that the characteristics of any isolator used in the design of seismic isolated structures are established according to test results conducted under certain loading conditions.

To fill the need for establishing the effect of loading history followed during the isolator tests on the isolator characteristics, this study investigates the variation in hysteretic behavior of an LRB subjected to different loading histories. For this purpose, the deteriorating bilinear hysteretic behavior of LRBs is used in the analytical idealizations and the corresponding results are discussed in terms of lead core temperature. In the analyses, selected parameters are velocity and amplitude of the loading history subjected to LRB.

2 Modeling of Deteriorating force-deformation relation

Experimental studies conducted with LRBs showed that LRBs subjected to cyclic motion experience a gradual reduction in strength that result in a deteriorating bilinear hysteretic force-deformation relation [9]. Fig. 2 presents hysteretic loops of a typical LRB subjected to cyclic motion. Accordingly, the initial strength of the bearing reduces with the initiation of motion. In order to idealize that variation in strength of LRBs, a mathematical model has been proposed by Kalpakidis and Constantinou [1] that considers the change in strength (or yield stress of lead) of LRBs due to instantaneous temperature of the lead core. The yield stress of lead which is defined as a function of lead core temperature is then used to determine the instantaneous strength of the bearing. Thus, this model makes it possible to have a deteriorating isolator strength through the exerted motion. 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 3 for geometrical features) whereas grey solid line stands for the analytically obtained response of the same bearing. It is clear that the deteriorating material model is highly accurate in simulating the actual behavior of LRBs without any calibration.
According to model proposed by Kalpakidis and Constantinou [1], the temperature rise in the lead core due to cyclic motion of LRBs, is calculated by the following set of equations:

\[
\frac{\delta T_L}{\delta t} = \frac{\sigma_{YL}(T_L,t)|Z|U}{\rho_L \cdot c_L \cdot h_L} - \frac{k_L \cdot T_L}{a \cdot \rho_L \cdot c_L \cdot h_L} \left( \frac{1}{F} + 1.274 \left( \frac{t_s}{a} \right) \left( \frac{t^*}{a^2} \right)^{1/3} \right)
\]

(4)

\[
F = \left\{ \begin{array}{ll}
2 \left( \frac{t^*}{\pi} \right) \frac{t^*}{\pi} & t^* < 0.6 \\
\frac{8}{3.14} \cdot \left( \frac{1}{2.4} \right)^2 \left[ 1 - \frac{1}{3 \cdot \left( 4 - t^* \right)^2} + \frac{1}{6 \cdot \left( 4 - t^* \right)^2} - \frac{1}{12 \cdot \left( 4 - t^* \right)^2} \right] & t^* \geq 0.6
\end{array} \right.
\]

(5)

\[

t^* = \frac{\alpha_s \cdot t}{a^2}
\]

(6)

\[
\sigma_{YL}(T_L) = \sigma_{YL0} \cdot \exp\left( -E_2 \cdot T_L \right)
\]

(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, \( \rho_L \) is the density of lead, \( c_L \) is the specific heat of lead, \( \alpha_s \) is the thermal diffusivity of steel, \( k_L \) is the thermal conductivity of steel, \( \sigma_{YL0} \) 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, namely \( h_L, a, \) and \( t_s \), the rest of the parameters are based on the material properties. These properties are given by Kalpakidis and Constantinou [1] as; \( \rho_L = 11200 \text{kg/m}^3, c_L = 130 \text{J/(kg} \cdot \text{C)}, k_L = 50 \text{W/(m} \cdot \text{C}), \alpha_s = 1.41 \times 10^{-4} \text{m}^2/\text{s}, E_2 = 0.0069/\text{C} \).
3 Properties of LRB used in parametric analyses

In this section, analyses are performed with the verified hysteretic behavior of a typical LRB (see Fig. 2) where the diameters of the bearing and the lead core are 950 mm and 254 mm, respectively. It consists of 29 layers of rubber (each layer is 7 mm thick) and 28 layers of steel (each layer is 3 mm thick). The total height, $h_L$, of the LRB is 287 mm. The analytically verified hysteretic behavior of the employed LRB [6] 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 [10] is quite satisfactory to represent the actual hysteretic behavior of the employed LRB obtained from test results, the same hysteretic representation is used in the parametric analyses.

In the following sections, the LRB under investigation is subjected to different loading patterns to identify the effects of i) velocity of loading; and ii) amplitude of loading. The comparative analyses of the investigated LRB under different loading patterns are presented in terms of the rise in the lead core temperature.
3.1 Effect of Loading Velocity

In order to determine the effect of loading velocity on lead core heating, 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 Ozdemir [6] where loading velocity is 20.8 mm/s, loading amplitude is 495 mm, and number of cycles is 3. In the analyses, to be able to find the effect of loading velocity, the amplitude of the loading (495 mm) and the number of cycle (3) are kept constant while the loading velocity 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 (1.5, 3.0, and 6.0 multiples of 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 heating is affected by variation in loading velocity. It is clearly seen that 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 amounts of loses in the initial strength of the considered LRB are in the order of 33% and 42%, 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, it can be said that slight changes in loading rate will result in negligible variation in hysteretic behavior of LRB. This can also be verified by comparing the corresponding force-displacement graphs presented in Fig. 5 where all of the curves are almost identical.
3.2 Effect of Loading Amplitude

To investigate the effect of loading amplitude on the performance of LRBs in terms of lead core temperature, LRB (see Fig. 2 for the corresponding force-deformation relation) is subjected to cyclic motions with various amplitudes when velocity of the loading (20.8mm/s) and number of cycle (3) is kept constant. Employed loading
patterns are presented in Fig. 6.a where the green line represents the displacement history subjected to LRB during the experiment.

![Force-displacement graphs of LRBs for loading amplitudes of (a)495mm (b)330mm (c)165mm (d)82.5mm.]

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 structural analysis program OpenSees [10] are given in Fig. 6.b. Each line in Fig. 6.b is represented by the same color used to identify the loading pattern given in Fig. 6.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%, respectively. It is clear that the rise in temperature of lead core depends highly on the amplitude of loading and the effect of lead core temperature at low amplitude motions can be neglected. Corresponding force-displacement graphs are given in Fig. 7. As can be seen in Fig. 7, as the amplitude of motion decreases, the force-displacement curves are obtained to be almost identical throughout the cyclic motion. Such 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 Conclusions

In this paper, a recently proposed mathematical model, that takes into account the gradual reduction in strength of LRBs 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 is studied as a function of loading history. Selected parameters to represent different loading conditions are namely, velocity and amplitude of the loading. Results of this study revealed the following conclusions:

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

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

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References