Lead-Core Heating Effect in Response of Bridges Isolated with LRBs

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SUMMARY:
The aim of this study is to show the effect of temperature dependent behavior of lead rubber bearings (LRBs) on the performance of seismic isolated bridges. Temperature dependent behaviour is represented by a recently proposed mathematical model that enables the modelling of deterioration in strength of the isolator under cyclic motion. Hence, an idealized bridge that is isolated with LRBs is subjected to excitations of near-field ground motions. During the analyses, effects of isolation period and characteristic strength of isolators are investigated. Nonlinear response history analyses are performed with both temperature dependent and independent hysteretic behavior of LRBs and corresponding maximum isolator displacements (MIDs) and maximum isolator forces (MIFs) are compared. Results of this study reveal that employing temperature independent hysteretic behavior of LRBs in the analyses leads to overestimated isolator displacements compared to ones where temperature dependent behavior of LRBs is considered.

Keywords: Lead-core heating, lead rubber bearings, nonlinear response history analyses, bounding analyses

1. INTRODUCTION

Nonlinear response history analyses of systems isolated by lead-rubber bearings (LRBs) have generally been conducted with representative bilinear hysteretic force-deformation relation. Properties of this bilinear representation are determined considering the lower and upper bound characteristics of the bearing. The difference between lower and upper bound characteristics emerges due to aging, contamination, history of loading, and heating effects. For LRBs, it is found that such a difference is mainly due to increase in temperature of lead-core under cyclic motion (Constantinou et al., 2007a; 2007b). Increase in temperature of lead-core results in reduction of the leads yield stress. A mathematical model to represent this phenomenon is proposed and verified by Kalpakidis and Constantinou (2009a; 2009b). Theory is based on estimation of instantaneous temperature increase in the lead core. Estimated temperature is then used to determine the gradual reduction in the yield stress of lead (also reduction in strength of the isolator), accordingly. As a result, LRBs can be represented by a deteriorating force-deformation relation instead of non-deteriorating one which is used through bounding analysis.

The objective of this study is to evaluate the effect of temperature-dependent hysteretic behavior of LRBs on the performance of SIBs in comparison to bounding analysis. Hence, an idealized bridge which is isolated with LRBs is subjected to excitations of near-field ground motions. These ground motion records are selected so that they sustain a distinct pulse-type behavior. During the analyses, effects of isolation period and characteristic strength of isolators are investigated. Nonlinear response history analyses are performed with both deteriorating and non-deteriorating hysteretic behavior of LRBs and corresponding maximum isolator displacements (MIDs) and maximum isolator forces (MIFs) are compared.

2. ANALYTICAL MODELING OF BRIDGE

The investigated bridge is a continuous, three-span, cast-in-place concrete box girder structure that is also studied by Constantinou et al. (2007a). The intermediate bent geometry of the bridge presented in Figure 2.1a consist of a cap beam on top of two round columns. The superstructure is isolated by means of two LRBs at each bent as shown in Figure 2.1a. Mass acting on the bent is determined through the tributary area of the superstructure on the bent and it is lumped at the mass center of superstructure. The total weight, W, of the system is 8335 kN.

The bent geometry under consideration was modeled in 2-D and it was performed in structural analysis program OpenSees (2009). The analytical modeling of the bridge bent is schematically represented in Figure 1.b. The bridge superstructure was assumed to have infinite in-plane rigidity (Dicleli, 2006) to enable a clear understanding of the response of LRBs only. Effect of uplift due to overturning moment was ignored in the modeling of seismic isolation units. Implemented LRBs are considered to be effective only in the horizontal direction.

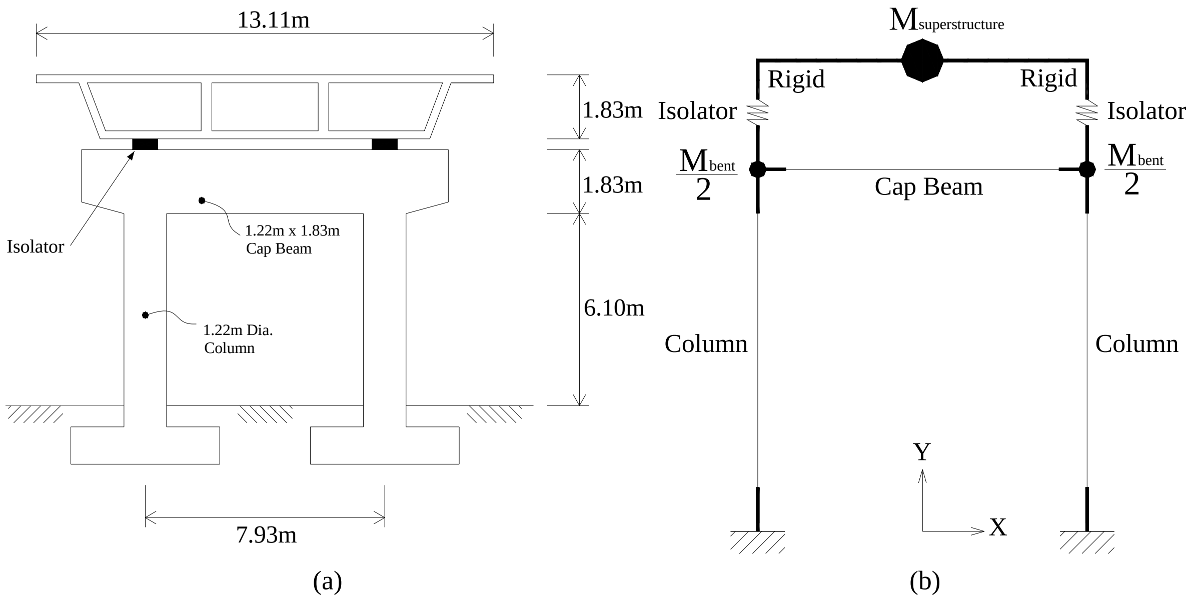

Figure 2.1 a) bent geometry of the sample bridge; b) analytical model of the bridge bent in 2-D.

3. MODELING OF ISOLATORS

LRBs employed in this study are represented by two distinct bilinear force-deformation relations. First one is a generic representation without considerations for cycle-to-cycle deterioration of properties whereas the second one considers the cyclic deterioration due to temperature rise in the lead core. For the first case, Q (characteristic strength), k_d (post-yield stiffness), and D_y (yield displacement) are the parameters needed to construct the non-deteriorating force-deformation relation given in Figure 3.1a. Variables F_y ($=Q+k_d x D_y$) and k_e ($=F_y/D_y$) are the yield force and elastic stiffness of the isolator, and can easily be determined by the given relations. Considered LRB characteristics are given in Table 3.1. The given Q/W ratios correspond to design values for lower bound analysis.

For the analyses where non-deteriorating bilinear representations are employed for LRBs, two sets of parameters were covered namely, lower and upper bound properties. The difference between lower and upper bound analyses is due to variation in the characteristic strength, Q, of isolators. Since Q is equal to $A_L x \sigma$, where A_L is the area of the lead core and σ is the yield stress of the lead, that variation emerges basically due to change in yield stress, σ. For an LRB, upper bound value is defined as the effective yield stress of the lead that is based on the first cycle of the bilinear hysteretic behavior. On the other hand, lower bound value is based on the average value of the effective yield stress of lead in the first three cycles. The effective yield stress value of the lead for lower bound analysis was selected as 10 MPa (Constantinou et al., 2007a). The relation between the yield stresses of the lead in the upper (σ_u) and lower (σ_l) bound cases was stated as σ_u=1.35σ_l (Constantinou et al., 2007a). Hence, the effective yield stress value of the lead for upper bound analysis was selected as 13.5 MPa, which is also used in the construction of deteriorating bilinear hysteresis as representative of the yield stress at first cycle and is updated (reduced) at each time instance due to temperature rise in the lead. The methodology describing the reduction in the strength of the LRBs is presented briefly in the following section.

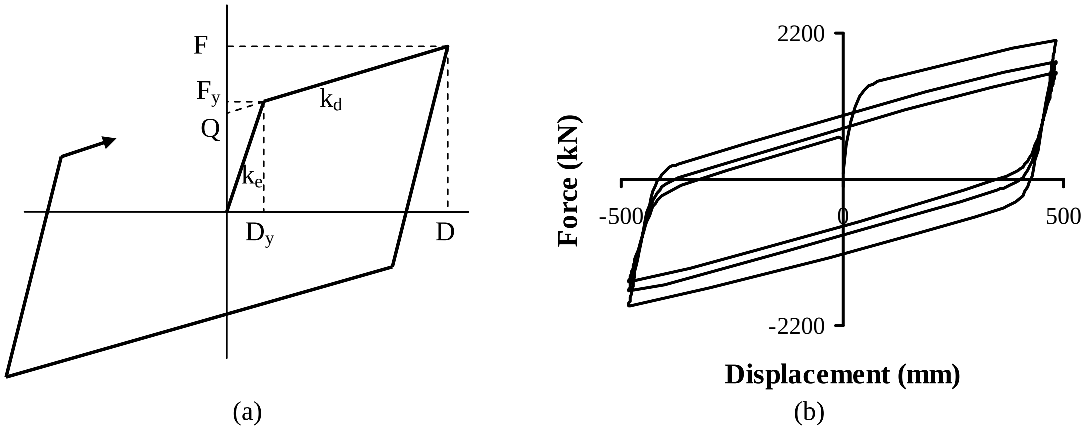

Figure 3.1 a) non-deteriorating and b) deteriorating (adopted from (Constantinou et al., 2007b)) force-deformation relations for LRBs.

Table 3.1 Isolator Characteristics used for the analyses.

Q/W ratio	T (sec)	R (mm)	F_y (kN)		b (k_d/k_e)	
			Lower	Upper*	Lower	Upper*
a= 103 mm; h_L= 353 mm; t_s= 150 mm						
0.08	2.0	864	375.2	491.9	0.112	0.085
	2.5	1016	360.1	476.8	0.074	0.056
	3.0	1219	351.9	468.6	0.053	0.040
	3.5	1524	347.0	463.6	0.039	0.030
a= 115 mm; h_L= 353 mm; t_s= 150 mm						
0.10	2.0	864	457.4	602.8	0.092	0.070
	2.5	1016	442.3	587.7	0.061	0.046
	3.0	1219	434.1	579.5	0.043	0.032
	3.5	1524	429.2	574.6	0.032	0.024
a= 126 mm; h_L= 353 mm; t_s= 150 mm						
0.12	2.0	864	540.7	715.3	0.077	0.059
	2.5	1016	525.6	700.2	0.051	0.038
	3.0	1219	517.4	692.0	0.036	0.027
	3.5	1524	512.4	687.0	0.027	0.020

*Also initial condition in temperature-dependent behavior

4. TEMPERATURE DEPENDENT BEHAVIOR OF LRBS

The mathematical model proposed by Kalpakidis and Constantinou (2009a) considers the variation in the characteristic strength (or yield stress of lead) of LRBs due to instantaneous temperature of the lead core. Figure 3.1b shows hysteretic behavior of a typical LRB tested under three fully reversed cycles at total design displacement. It clearly demonstrates the reduction in strength of an LRB from cycle-to-cycle due to heating effect in the lead core. In the model proposed by Kalpakidis and Constantinou (2009a), the force carried by LRB (F_y) under uni-directional loading is calculated by Equation 2.

$$F_y = k_d \cdot D + \sigma_{YL}(T_L) \cdot A_L \cdot Z \tag{4.1}$$

where $\sigma_{YL}(T_L)$ is the yield stress of lead based on the instantaneous temperature of lead core, A_L is the cross-sectional area of the lead core, D is the deformation of LRB, and Z is the hysteretic dimensionless quantity and satisfy the first-order differential equation given below:

$$D_y \cdot \dot{Z} = \left(A - |Z|^2 B \cdot \left(1 + sgn\left(\dot{D} \cdot Z \right) \right) \right) \cdot \dot{D} \tag{4.2}$$

where A and B are dimensionless quantities that control the shape and size of the hysteretic loop of the bearings, $\dot{D}$ is the relative velocity of bearing, and sgn stands for the signum function. Relation between A and B is selected as A=2B (Constantinou et al., 1987) so that Z is bounded between +1 and -1 when yielding occurs (Nagarajaiah et al., 1989). Hence, A and B are 1 and 0.5, respectively.

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

$$\dot{T}_L = \frac{\sigma_{YL}(T_L) \cdot \left| Z \cdot \dot{D} \right|}{\rho_L \cdot c_L \cdot h_L} - \frac{k_s \cdot T_L}{a \cdot \rho_L \cdot c_L \cdot h_L} \cdot \left(\frac{1}{F} + 1.274 \cdot \left(\frac{t_s}{a} \right) \cdot \left(t^+ \right)^{-1/3} \right) \tag{4.3}$$

$$F = \begin{cases} 2 \cdot \left(\dfrac{t^+}{\pi} \right)^{1/2} - \dfrac{t^+}{\pi} \cdot \left[2 - \left(\dfrac{t^+}{4} \right) - \left(\dfrac{t^+}{4} \right)^2 - \dfrac{15}{4} \cdot \left(\dfrac{t^+}{4} \right)^3 \right], & t^+ < 0.6 \\ \dfrac{8}{3 \cdot \pi} - \dfrac{1}{2 \cdot \left(\pi \cdot t^+ \right)^{1/2}} \cdot \left[1 - \dfrac{1}{3 \cdot \left(4 \cdot t^+ \right)} + \dfrac{1}{6 \cdot \left(4 \cdot t^+ \right)^2} - \dfrac{1}{12 \cdot \left(4 \cdot t^+ \right)^3} \right], & t^+ \geq 0.6 \end{cases} \tag{4.4}$$

$$t^+ = \frac{\alpha_s \cdot t}{a^2} \tag{4.5}$$

$$\sigma_{YL}(T_L) = \sigma_{YL0} \cdot exp(-E_2 \cdot T_L) \tag{4.6}$$

In the above equations, h_L is the height of lead, a is the radius of lead, t_s is the total shim 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. In this study, σ_{YL0} is identical with σ_u and equals to 13.5 MPa.

5. SELECTION AND SCALING OF NEAR-FIELD GROUND MOTIONS

Considered ground motion set is composed of near-field records with distinct pulse-type behavior and taken from the study of Gunay and Sucuoglu (2009). There are 50 ground motion records of which the average shear wave velocities are between 180 m/s and 360 m/s. Closest distances (d) of the selected

records to the fault rupture are less than 20 km and their moment magnitudes (M_w) are in between 6.1 and 7.6. Corresponding 5% damped spectra of the selected records with their mean value are depicted in Figure 5.1a.
In this study, considered scaling procedure consists of two complementary phases. In the first phase, selected records are individually scaled to match the spectral acceleration of the corresponding target spectrum at a period of 2.25 sec. This value is stated to be appropriate for period of an isolated structure and is an intermediate value in the period range of 1.5 sec. to 3 sec. where most of the isolated structures are designed (2006). In the second phase, mean of the scaled records in the first phase are further scaled to achieve the criterion defined in ASCE (2005) that is the mean spectra of all records does not fall below 1.3 times the target spectrum by more than 10%. The target spectrum and the scaled mean spectrum are given in Figure 5.1b.

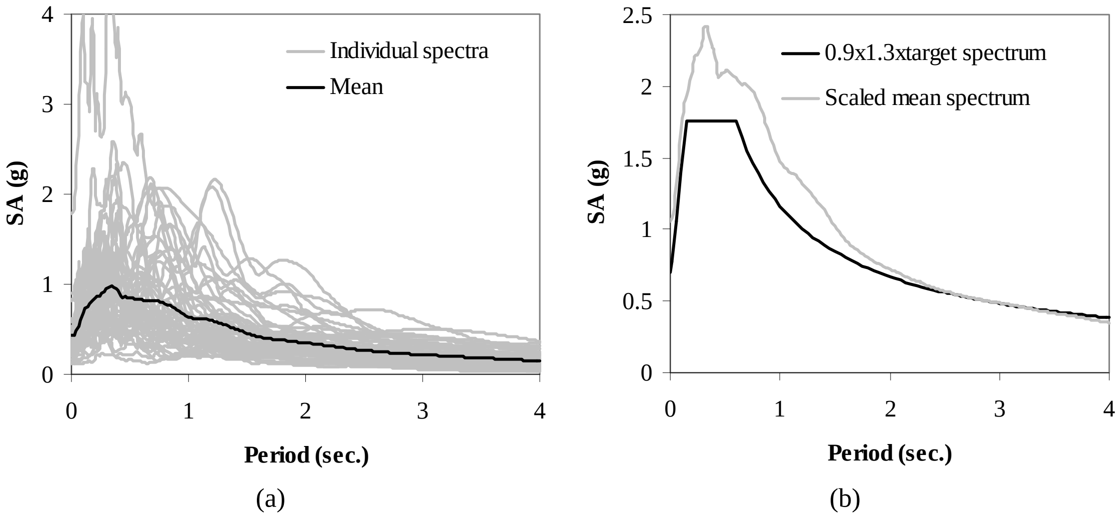

Figure 5.1 a) 5% damped acceleration spectra of the selected ground motions; b) target spectrum and mean spectrum of ground motions after scaling.

Values of the scaling factors should be carefully selected in order not to introduce any bias to the results. In a recent study, it has been stated that scaling factors should be less than ten for unbiased results (Hancock et al., 2008). In accordance with that conclusion, minimum, maximum, and average scaling factors used in the present study are, respectively, 0.77, 7.33, and 2.7.

6. ANALYSES RESULTS

The probable variations in MIDs and MIFs, when lower and upper bound properties of LRBs are used in the analyses instead of temperature dependent deteriorating properties, are studied. Results obtained by using the deteriorating properties are compared with that of lower bound analysis in terms of MIDs and with upper bound analysis in terms of MIFs. Since the upper bound values usually result in the largest force demand on the substructure elements, results obtained from analyses performed with upper bound characteristics are used to compare MIFs. On the other hand, the lower bound values result in the largest displacement demand on the isolators. Thus, results obtained from analyses performed with lower bound characteristics are used to compare MIDs.

Before giving the results in a comparative way, Figure 6.1 is depicted to clarify the variation in the response of an SIB when temperature dependent behavior of an LRB is employed instead of following the bounding analyses. The characteristic strengths used in the analyses of lower and upper bound analyses are 333kN and 450kN, respectively. The post-yield stiffness, k_d, is equal to 1865kN/m (T=3.0s). The characteristic strength employed for upper bound analysis is also used as the initial strength for temperature dependent analysis. Considered isolation systems are subjected to excitation of 230^{o} component of El Centro array #6 with a scale factor of 1.57. While hysteretic loops of the considered cases are shown in Figure 6.1a, the corresponding temperature rise in the lead core calculated in accordance with Equations (4.3)-(4.6) is given in Figure 6.1b. The temperature dependent behavior of LRB given in Figure 6a is represented by the term “Heating Included” as in the rest of the study.

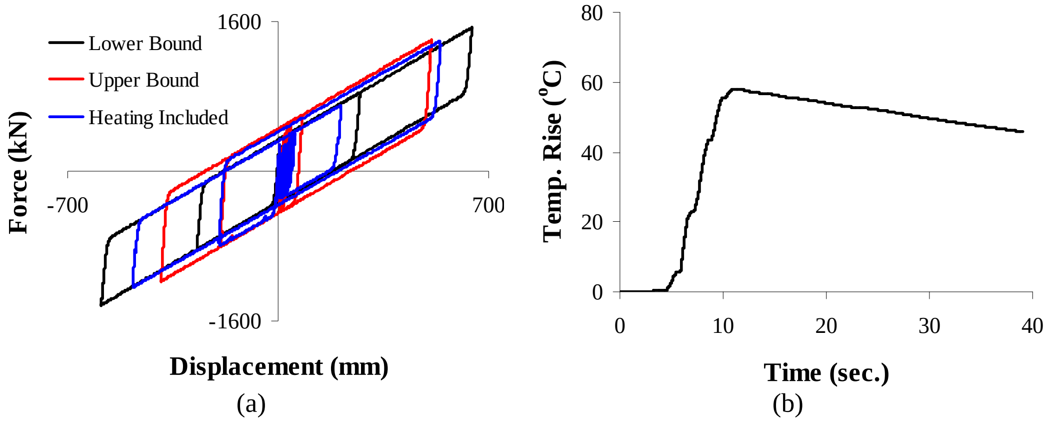

Figure 6.1 a) Hysteresis loops for lower bound, upper bound, and heating included cases; b) corresponding temperature rise in the lead core.

6.1 Effect of Isolation Period *T*

In this section, effect of lead core heating on the variation of response of the considered SIB is studied as a function of isolation period, *T*. For this purpose, *Q*/*W* ratio is kept constant (*Q*/*W*=0.10) while *T* varies (selected as 2.0s, 2.5s, 3.0s, and 3.5s). Comparisons of MIDs are presented in Figure 6.2, while Figure 6.3 presents the comparison of results in terms of MIFs.

In Figure 6.2, MIDs corresponding to lower bound analyses are given in the horizontal axis while the vertical axis stands for MIDs obtained from analyses considering deteriorating properties and represented under the name of “heating included”. Black solid lines in those figures have 45^{o} slope and represent the cases where the given values in both horizontal and vertical axes of the graph are identical. In Figures 6.2, it is clear that the response of isolators, in terms of MIDs, obtained from lower bound analyses and the heating included cases differentiates from each other. MIDs corresponding to lower bound analyses are higher than the ones regarding the temperature dependent behavior by being under the black solid lines, regardless of the isolation period. Average of MIDs obtained from analyses performed by lower bound characteristics are higher than those of heating included cases by amounts of 11%, 12%, 12%, and 13% when isolation periods are 2.0s, 2.5s, 3.0s, and 3.5s, respectively. Although the amount of overestimation in MIDs is more than 10% when bounding analyses is compared to heating included cases, the dependency of results on isolation period can be negligible. The similar comparison is discussed for MIFs through Figure 6.3. Figure 6.3 indicates that regardless of the isolation period, there is almost a perfect match between the results obtained by considering the heating included case and upper bound properties. This implies that the seismic force on the isolation units calculated by upper bound analyses and temperature dependent behavior are in good agreement.

6.2 Effect of *Q*/*W* Ratio

In this section, effect of lead core heating on the variation of response of the considered SIB is studied as a function of *Q*/*W* ratio. For this purpose, *T* is kept constant (*T*=3.0s) while *Q*/*W* ratio varies (selected as 0.08, 0.10, and 0.12). Comparisons of MIDs are presented in Figure 6.4, while Figure 6.5 presents the comparison of results in terms of MIFs.

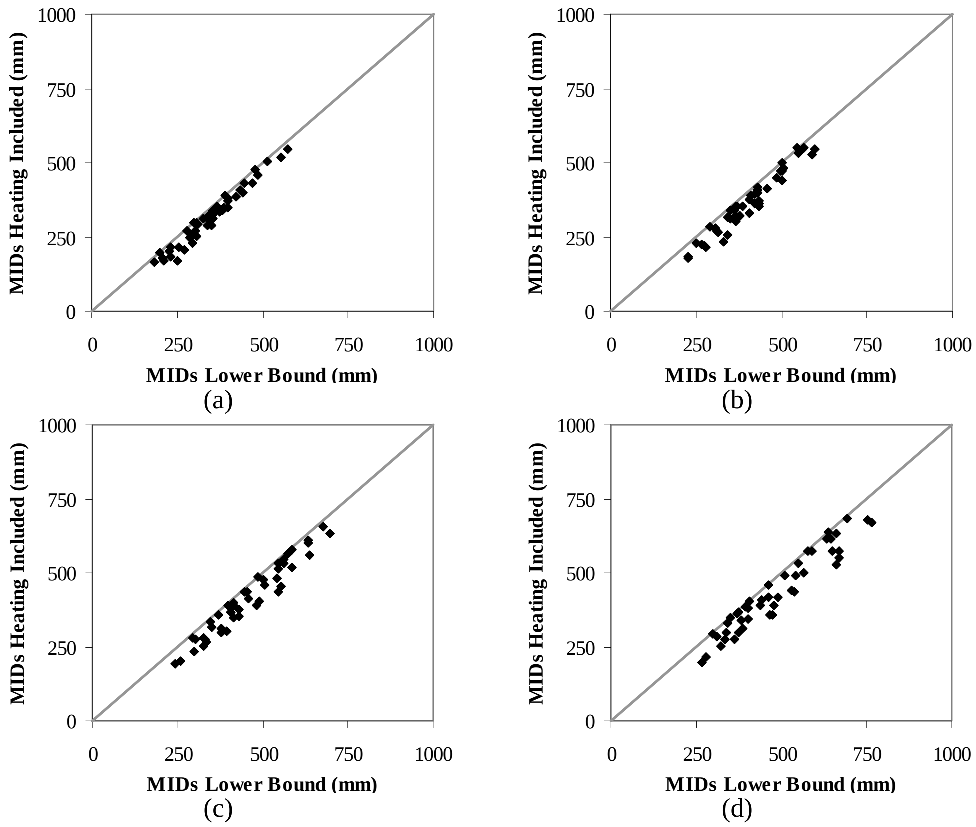

Figure 6.2 Comparison of MIDs obtained from analyses considering lower bound and heating included cases for a)T=2.0s; b)T=2.5s; c)T=3.0s; and d)T=3.5s.

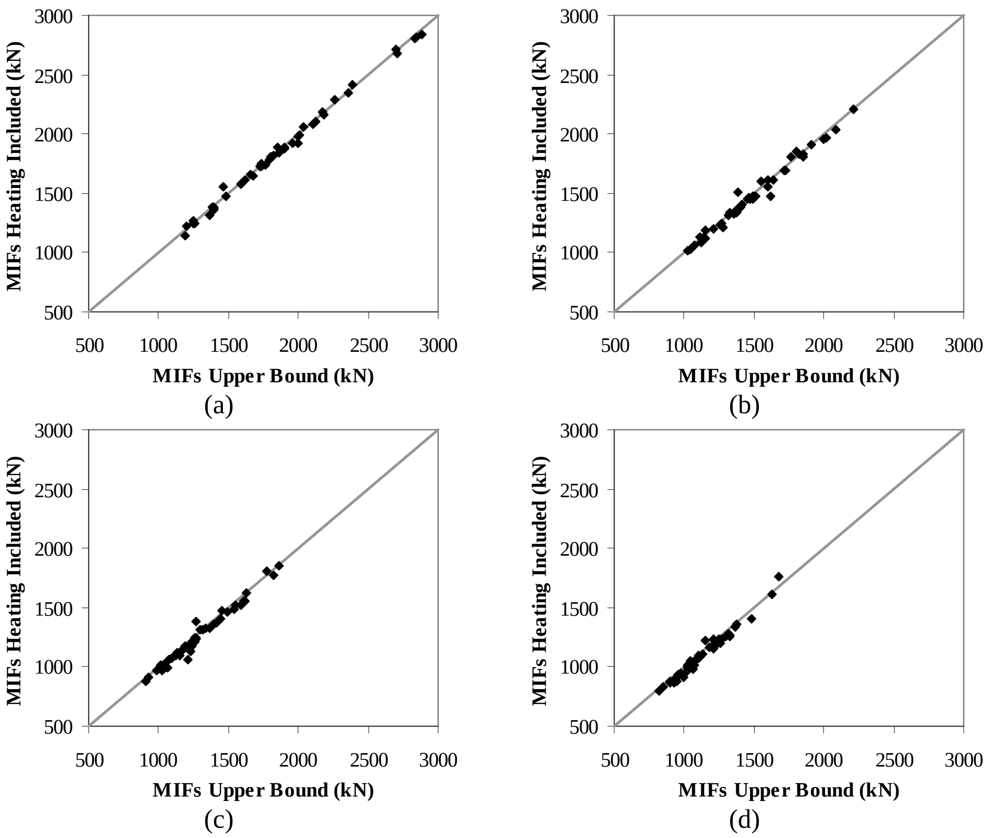

Figure 6.3 Comparison of MIFs obtained from analyses considering upper bound and heating included cases for a)T=2.0s; b)T=2.5s; c)T=3.0s; and d)T=3.5s.

In Figure 6.4, it is clearly seen that MIDs, obtained from lower bound analyses are higher than those of heating included cases regardless of the *Q*/*W* ratio. The amounts of overestimation when bounding analyses are compared with heating included cases are 10%, 12%, and 17% for *Q*/*W* ratios of 0.08, 0.10, and 0.12, respectively. Unlike the effect of isolation period, *T*, temperature dependent behavior of LRBs is sensitive to change in *Q*/*W* ratio. Amount of overestimation in MIDs increases as *Q*/*W* ratio increases. Figure 6.5 presents the similar comparison for MIFs and it indicates that there is almost a perfect match between the results obtained by considering the heating included case and upper bound properties for all of the considered *Q*/*W* ratios.

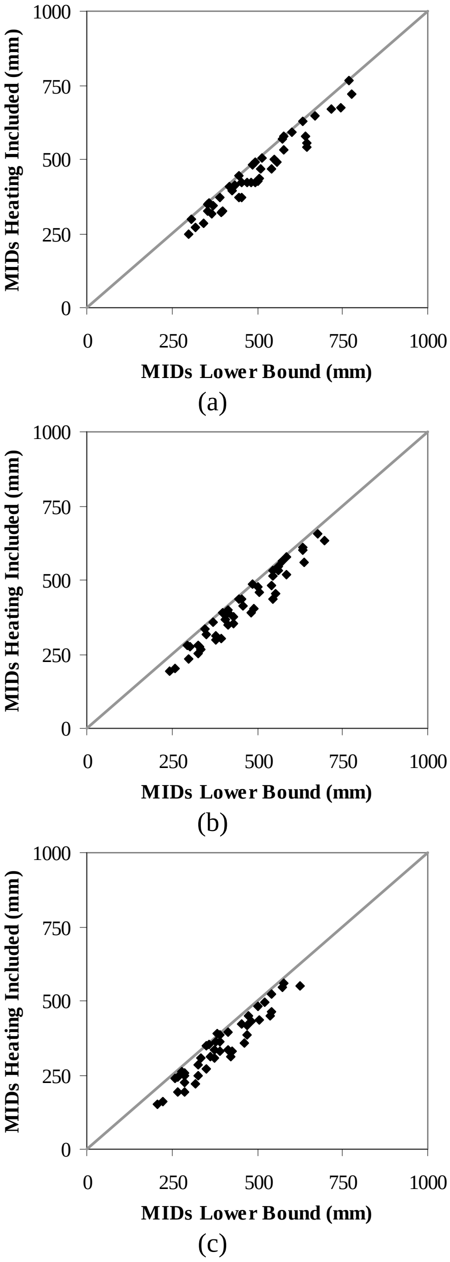

Figure 6.4 Comparison of MIDs obtained from analyses considering lower bound and heating included cases for a)Q/W=0.08; b)Q/W=0.10; c)Q/W=0.12.

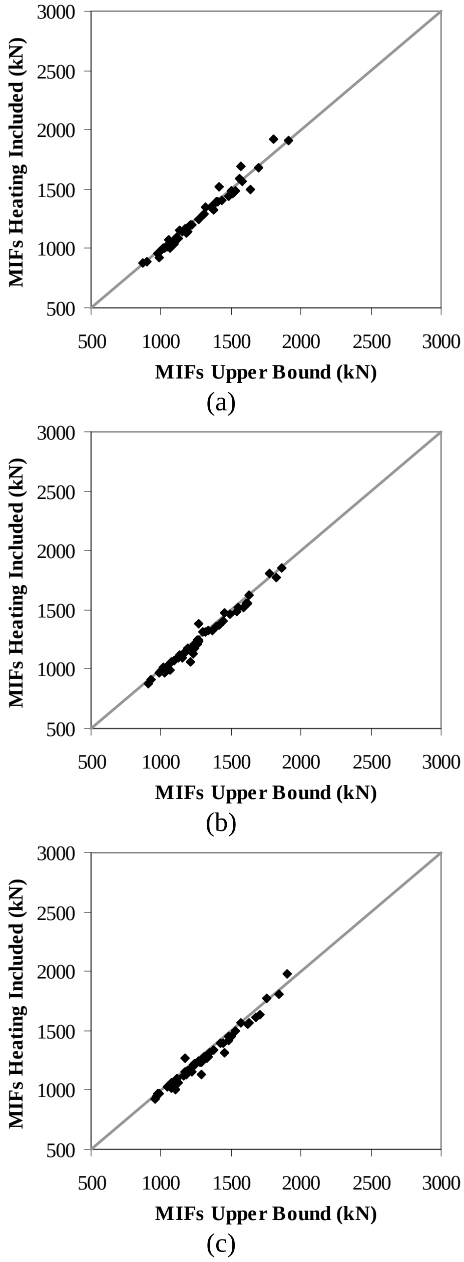

Figure 6.5 Comparison of MIFs obtained from analyses considering upper bound and heating included cases for a)Q/W=0.08; b)Q/W=0.10; c)Q/W=0.12.

7. CONCLUSIONS

This paper focused on the response of SIBs when temperature dependent behavior for LRBs are of concern. Considered temperature dependent behavior enables the modeling of deterioration in isolator strength under cyclic motion due to temperature rise in the lead core. Performance of SIBs is studied in a comparative way with due consideration of bounding (upper and lower bound) analysis that is used to incorporate the heating effect. In this sense, considered SIBs subjected to near-field ground motions with distinct pulse-type behavior. Nonlinear response-history analyses were conducted in OpenSees in which the temperature dependent hysteretic model of LRBs is implemented. Comparisons are done considering various isolation periods (2.0, 2.5, 3.0, and 3.5 sec.) and Q/W ratios (0.08, 0.10, and 0.12). Maximum isolator displacements and maximum isolator forces are the structural response quantities considered in the comparisons between bounding analysis and temperature dependent behavior.

The study presented here led to the conclusions that (i) MIFs obtained by the temperature dependent hysteretic behavior of LRBs perfectly match the ones obtained from bounding analyses using the upper bound properties (ii) MIDs obtained from bounding analyses using the lower bound properties overestimate the MIDs obtained by temperature dependent hysteretic behavior of LRBs. This indicates that using lower bound properties of lead core results in conservative estimates for response quantities of SIBs. The amount of this conservatism basically depends on Q/W ratio which is directly related to the radius and effective yield stress of the lead core. As Q/W ratio increases, amount of overestimation increases regardless of the isolation period.

REFERENCES

Constantinou, M.C., Whittaker, A.S., Fenz, D.M. and Apostolakis, G. (2007). *Seismic isolation of bridges*. Report submitted to the State of California Department of Transportation, Department of Civil, Structural and Environmental Engineering, State University of New York at Buffalo.

Constantinou, M.C., Whittaker, A.S., Kalpakidis, I.V., Fenz, D.M. and Warn, G.P. (2007). *Performance of seismic isolation hardware under service and seismic loading*. Technical Report MCEER-07-0012, Multidisciplinary Center for Earthquake Engineering Research, Department of Civil, Structural and Environmental Engineering, State University of New York at Buffalo.

Kalpakidis, I.V. and Constantinou, M.C. (2009). Effects of heating on the behavior of lead-rubber bearing. I:theory. *Journal of Structural Engineering* (ASCE), **135:12**, 1440-1449.

Kalpakidis, I.V. and Constantinou, M.C. (2009). Effects of heating on the behavior of lead-rubber bearing. II:verification of theory. *Journal of Structural Engineering* (ASCE), **135:12**, 1450-1461.

Open System for Earthquake Engineering Simulation (OpenSees) (2009). Version 2.1.0, Pacific Earthquake Engineering Research Center, http://opensees.berkeley.edu.

Dicleli, M. (2006). Performance of seismic-isolated bridges in relation to near-fault ground-motion and isolator characteristics. *Earthquake Spectra*, **22:4**, 887-907.

Constantinou, M.C. and Adnane, M.A. (1987). *Dynamics of soil-base-isolated structure systems: evaluation of two models for yielding systems*. Report to NSF, Department of Civil Engineering, Drexel University, Philadelphia.

Nagarajaiah, S., Reinhorn, A.M. and Constantinou, M.C. (1989). *Nonlinear Dynamic Analysis of Three-Dimensional Base Isolated Structures* (*3D-BASIS*). Technical Report NCEER-89-0019, National Center for Earthquake Engineering Research, State University of New York at Buffalo.

Gunay, M.S. and Sucuoglu, H. (2009). Predicting the seismic response of capacity-designed structures by equivalent linearization. *Journal of Earthquake Engineering*, **13:5**, 623-649.

Tena-Colunga, A. and Perez-Osornia, M.A. (2006). Design displacements for base isolators considering bidirectional seismic effects. *Earthquake Spectra*, **22:3**, 803-825.

American Society of Civil Engineers (ASCE) (2005). *Minimum Design Loads for Buildings and Other Structures*. Standard ASCE/SEI 7-05, Reston, VA.

Hancock, J., Bommer, J.J. and Stafford, P.J. (2008). Numbers of scaled and matched accelerograms required for inelastic dynamic analyses. *Earthquake Engineering and Structural Dynamics*, **37:14**, 1585-1607.