Modeling of Lead Rubber Bearings via 3D-BASIS, SAP2000, and OpenSees Considering Lead Core Heating Modeling Capabilities

Zafer Kanbir
Istanbul University, Department of Civil Engineering, Istanbul, Turkey
Email: zaferkanbir@yahoo.com

Gökhan Özdemir
Anadolu University, Department of Civil Engineering, Eskisehir, Turkey
Email: gokhan_ozdemir@anadolu.edu.tr

Cenk Alhan
Istanbul University, Department of Civil Engineering, Istanbul, Turkey
Email: cenkalhan@istanbul.edu.tr

***Abstract*—Seismic isolation systems can be modeled in various structural analysis programs using nonlinear or equivalent linear properties of isolators. The effort required and the accuracy of the results depend on the program and the modeling method used. In this study, three commonly used structural analysis programs, namely SAP2000, 3D-BASIS, and OpenSees, are studied considering modeling of Lead Rubber Bearings (LRBs) by means of linear and nonlinear representations. Base displacement (BD) and top floor acceleration (TFA) responses obtained from time history analyses under Kocaeli and Chi-chi earthquakes are compared. In case of nonlinear analyses, the temperature-dependent behavior of LRBs is modeled in OpenSees only, because of the inability of the other programs mentioned above in capturing the associated strength deterioration. It is revealed that there exists no significant difference between the analysis results of three programs with the exception of the case where the temperature-dependent behavior of LRBs is of concern. It is found that there may be significant differentiation in structural response when the temperature-dependent behavior of LRBs is considered depending on the earthquake level which could have been confirmed by OpenSees program, only.**

***Index Terms*—seismic isolation, modeling of isolation systems, lead rubber bearings, lead core heating.**

I. Introduction

The main aim of earthquake engineering is to protect structural and non-structural components of structures and their contents from detrimental effects of earthquakes. This can be achieved by minimizing inter-story drifts and floor accelerations under strong ground motions which may both be obtained by using seismic isolation. Seismic isolation provides decoupling of the structure from earthquake effects by concentrating the displacements at the flexible isolation system [1]. One of the widely used seismic isolation bearing type is the rubber bearing. Due to the low damping nature of the natural rubber, rubber bearings are generally used with one or more lead cores, which are called Lead Rubber Bearings (LRBs).

The characteristic strength, which is among the important properties of LRBs, deteriorates as the number of displacement cycles in LRBs increase when subjected to lateral cyclic motion. Although this phenomenon was discovered a long time ago by experimental studies [2], only recently Kalpakidis and Constantinou [3], [4] have developed and verified a mathematical theory that calculates the reduction in characteristic strength and the energy dissipated per cycle due to the heating of the lead core in LRBs. The main principle of the theory is predicting instantaneous temperature and relating this to the characteristic strength of the isolator. Although the LRBs are typically modeled with non-deteriorating force displacement properties for ease of modeling, the importance of strength deterioration due to lead core heating was emphasized in recent studies [5].

Even though seismic isolators can be modeled in many structural analysis programs including SAP2000 [6] and 3D-BASIS [7] that enable simple modeling with two-node discrete elements, they cannot capture the complex behavior such as the strength deterioration observed during the cyclic motion of LRBs which on the other hand can be modeled by the open-source structural analysis program OpenSees [8]. In this study, modeling of structures seismically isolated by LRBs by means of both linear and nonlinear idealizations via three widely used structural analysis programs, namely SAP2000, 3D-BASIS, and OpenSees is described and structural response of a representative structure obtained from time history analyses performed by these structural analyses programs are compared [9].

Manuscript received February 3, 2018; revised August 19, 2018.

doi: 10.18178/ijscer.7.4.294-301

II. Structural Model and Earthquake Records

A. Structural Model

A four-story frame type generic building representing low-rise reinforced concrete buildings is selected for the analysis [10] (Fig. 1). The basement and each floor of the superstructure have the same mass of 400 tons, which are lumped at the center of mass of each floor in the analysis model. The concrete is selected to have an elastic modulus of E = 32000 Mpa. The fundamental fixed base periods are 0.5 s, 0.5s, and 0.4s in the lateral and rotational directions, respectively.

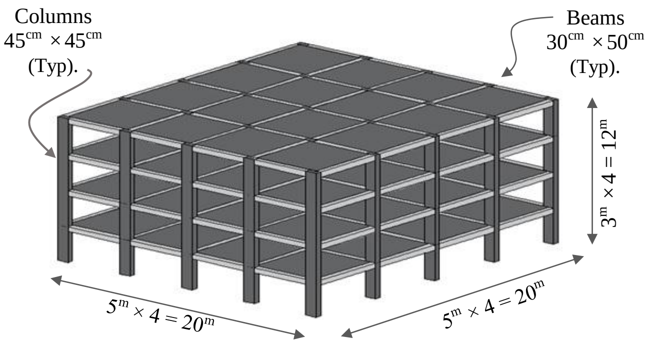

Figure 1. 3D view of the analyzed superstructure.

In the isolation system, there are a total of 25 bearings, one located underneath each column. It is assumed that the vertical loads on all isolators are equal. It is sufficient to define the hysteretic properties of the isolators without considering the geometric features of the isolators for SAP2000 and 3D-BASIS. On the other hand, the actual geometric dimensions and material properties of the isolators have to be defined explicitly in OpenSees model which takes the heating effects of the lead core into account. Thus, it is necessary to design the bearings with their physical and material properties for modeling in OpenSees. In this study, the design of the bearing is performed by following the procedure presented in Constantinou et al. [11]. Non-linear hysteretic properties of bearings namely characteristic strength, q, post-elastic stiffness, k_D, initial stiffness, k_I, yield displacement, D_y, and yield force, f_y, are calculated by the equations given below, here, A_L and A_r are the areas of the lead and the rubber, respectively and all other variables are defined in Table I which presents the geometrical and mechanical properties of designed LRB.

$$q = \sigma_{YL0} A_L \tag{1}$$

$$k_D = \frac{GA_r}{T_r} \tag{2}$$

$$k_I = \frac{k_D}{r} \tag{3}$$

$$q = (k_I - k_D)\, D_y \tag{4}$$

$$f_y = k_I \times D_y \tag{5}$$

B. Modeling of Temperature-Dependent Behavior of Lead Rubber Bearings

In this study, the mathematical model proposed by Kalpakidis and Constantinou [3], is utilized in OpenSees model for taking the heating effects of the lead core into account. According to this model, the yield stress of lead σ_{YL} deteriorates as the temperature increases. The instantaneous yield stress is defined by the following equation.

$$\sigma_{YL} = \sigma_{YL0} \exp(-E_2 \times T_L) \tag{6}$$

where E_2 is a constant and T_L is the increase in the lead core temperature with respect to the initial temperature. The only unknown in (6) is the temperature rise, T_L and it is calculated by (7), (8) and (9), where a is the radius of lead, h_L is the height of lead core, ρ_L is the density of lead, c_L is the specific heat of lead, α is the thermal diffusivity of steel, k_s is the thermal conductivity of steel, t is the time since the beginning of the motion and t^+ is the dimensionless time. The material properties are given by Kalpakidis and Constantinou [3], as ρ_L = 11200 kg/m^3, c_L = 130 J/(kg ℃), k_s = 50 W/(m°C), α = 1.41x10^{-5} m^2/s, and E_2 = 0.0069/ ℃.

C. Earthquake Records

Two strong ground motion data obtained from PEER Ground Motion Database [12] are used in the unidirectional time history analyses of the modeled structure. These records are Izmit and TCU065 recorded in the 1999 Kocaeli, Turkey and the 1999 Chi-Chi, Taiwan Earthquakes, respectively. Moment magnitudes of the earthquakes are 7.51 and 7.62, and the peak ground accelerations are 0.24g and 0.79g for Izmit and TCU065 records, respectively. 20% damped acceleration and displacement response spectra of these strong ground motion records are presented in Fig. 2.

TABLE I. Geometrical and Mechanical Properties of Designed Lead Rubber Bearing

Bonded diameter of bearing, D_B	520 mm
Diameter of lead core, D_L	75 mm
Total rubber thickness, T_r	260 mm
Number of rubber layers, n	18
Rubber layer thickness, t	14.4 mm
Steel shim thickness, t_s	2.0 mm
Initial yield stress of lead, σ_{YL0}	10 MPa
Shear modulus of rubber, G	0.5 MPa
Characteristic strength, q	44.18 kN
Post elastic stiffness, k_D	399.91 kN/m
Post elastic to initial stiffness ratio, r	0.1
Yield force, f_y	49.09 kN
Yield displacement, D_y	12.3 mm

$$\frac{dT_L}{dt} = \frac{\sigma_{YL}(T_L)\times\nu(t)}{\rho_L c_L h_L} - \frac{k_s \times T_L}{a \times \rho_L c_L h_L} \times \left(\frac{1}{F} + 1.274 \times \left(\frac{t_s}{a}\right) \times (t^+)^{-1/3}\right) \tag{7}$$

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

$$t^+=\frac{\alpha\times t}{a^2} \tag{9}$$

III. Modeling and Analysis of Nonlinear Isolation Systems

A. Modeling via 3D-BASIS

3D-BASIS is a special-purpose program developed to perform nonlinear dynamic analysis of seismically isolated structures. While the first version of the program was designed for analysis of single-superstructure systems, it was later updated to analyze multiple superstructures on a common base and was named as 3D-BASIS-M [13]. The program assumes that the superstructure remains linear elastic. There are two options for modeling the superstructure; one of them is three-dimensional shear building representation while the other one is full three-dimensional representation. For shear building representation, the story stiffnesses are defined. For full 3D representation, the input includes eigenvalues and eigenvectors of the fixed-base model. The isolation system can be modeled as linear or nonlinear. The isolation system elements that can be modeled in 3D-BASIS include low damping rubber bearings, high damping rubber bearings, LRBs, lead extrusion devices, and mild steel dampers. The strength deterioration in LRBs due to lead core heating during cyclic motion cannot be modeled in 3D-BASIS which also does not have a visual interface.

In this study, full three-dimensional representation is used for the superstructure and the required eigenvalues and eigenvectors are obtained from the analysis performed for the fixed-base superstructure in Sap2000. In program 3D-BASIS, superstructure and isolation system damping can be defined separately. In the analysis, the superstructure damping ratio is taken as 2%. The hysteretic element is used to model the non-linear isolation system elements. For such an element, the values of r, f_y, and D_y are the input arguments.

B. Modeling via SAP2000

Sap2000 is a finite element program that performs two or three-dimensional static and dynamic analyses of structures. It has a visual interface in which the isolators are modeled with link /support elements with two nodes connected by six springs. Linear bearing, low damping rubber bearing, lead rubber bearing, flat sliding bearing, double and triple frictional pendulum bearings are some of the isolator types that can be modeled using the available features in SAP2000. It is beyond the ability of SAP2000 to model the temperature-dependent behavior of LRBs, too.

Rubber bearing type link/support element is used to model nonlinear behavior of lead rubber bearing in this study. For nonlinear rubber bearing, bilinear force-deformation properties including k_I, f_y, and r, should be defined in two horizontal directions, but only linear elastic properties can be defined for the axial and three rotational directions.

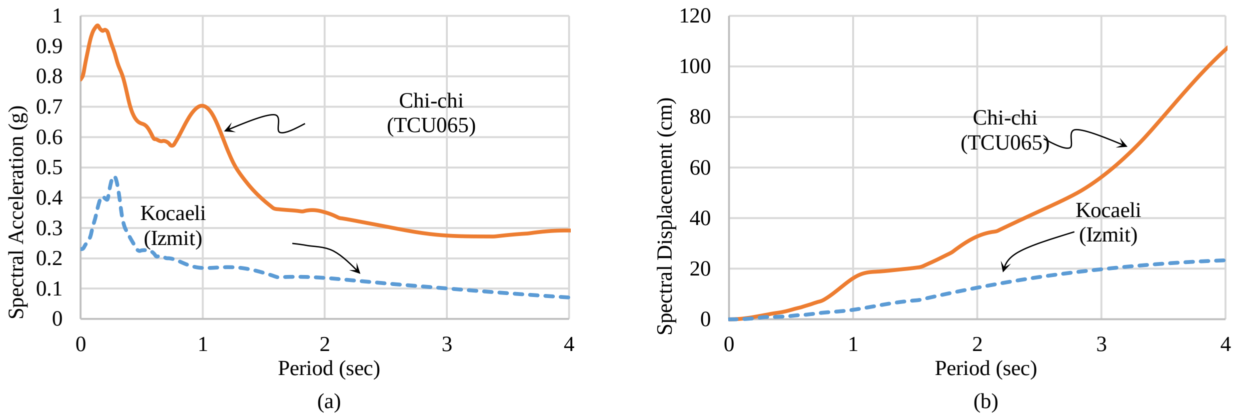

Figure 2. (a) Acceleration and (b) Displacement response spectra (20 % damped).

For direct integration analysis, which is used in this study, the damping of the superstructure can be assigned separately. For this purpose, modal damping must be used and the damping of the first three modes (rigid body modes) must be set to zero because the inherent damping of the isolators is defined by their hysteretic properties. The modal damping ratios for modes of the superstructure are taken as 0.02. Three-dimensional model of the building in SAP2000 is shown in Fig. 3.

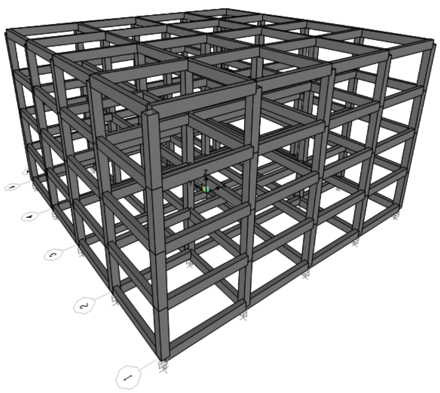

Figure 3. Three-dimensional model of the structure in SAP2000.

C. Modeling via OpenSees

TABLE II. DESCRIPTION OF THE USER INPUT ARGUMENTS FOR LEADRUBBERX

Required Input*	Optional Input**
Element tag	Vector components defining local x-axis
First node tag of the element	Vector components defining local y-axis
Second node tag of the element	Cavitation parameter [10]
Yield stress of bearing	Damage parameter [0.5]
Post-yield stiffness ratio	Strength reduction parameter [1]
Shear modulus of rubber	Shear distance ratio [0.5]
Bulk modulus of rubber	Mass of the bearing [0]
Lead core diameter (or internal diameter)	Viscous damping parameter [0]
Outer diameter	Cover thickness [0]
Single shim layer thickness	Density of lead [11200 kg/m^3]
Single rubber layer thickness	Specific heat of lead [130 J/kg ℃]
Number of rubber layers	Thermal conductivity of steel [50 W/m ℃]
	Thermal diffusivity of steel [1.41x10^{-5} m^2/s]
	Tag to include cavitation and post-cavitation [0]
	Tag to include buckling load variation [0]
	Tag to include horizontal stiffness variation [0]
	Tag to include vertical stiffness variation [0]
	Tag to include strength deterioration due to heating of lead core [0]

* No default values exist.
** Default values -if exist- are given in brackets.

The OpenSees program is an open-source finite element software designed to develop applications for simulating the performance of structural and geotechnical systems exposed to earthquake. The program provides advanced possibilities for modeling and analyzing the nonlinear behavior of structures, with a wide variety of options for material models, building elements, and solution algorithms. Currently, there are several element models that can be used to idealize hysteretic behavior of LRBs in the program library, but only LeadRubberX [14] takes into account the heating effects in the lead core. LeadRubberX element can only be used in three-dimensional models in OpenSees. The input arguments of the element include geometrical and material properties of lead rubber bearings. The details of input arguments are summarized in Table II.

There is also a Matlab [15] based graphical user interface called OpenSees Navigator which was developed by Schellenberg et al. [16]. This visual interface software is useful in modeling and displaying the analysis results. In the modeling of the isolated building, the OpenSees Navigator software is used in this study.

Rayleigh damping should be defined for the superstructure due to the absence of the option for modal damping in OpenSees. Hence, stiffness-proportional Rayleigh damping is assigned to the model in such a way that the damping ratio of the first mode of the fixed base structure is 0.02. Three-dimensional model of the building in OpenSees Navigator is presented in Fig. 4.

D. Analysis Results of Nonlinear Isolation System without Lead Core Heating Effects

The benchmark building described in section II-A is modeled via SAP2000, 3D-BASIS, and OpenSees with nonlinear seismic isolation systems but without taking lead core heating effects into account and time history analyses are conducted under earthquake records described in section II-C. Time variation of base displacements (BDs) and top floor accelerations (TFAs) obtained from the analyses with Izmit record are given in Fig. 5a and 5c, respectively. The peak value of BD is about 0.11 m for each of the three programs. The peak values of TFAs are obtained as 2.6, 2.2, and 2.6 m/s^2 for SAP2000, 3D-BASIS, and OpenSees, respectively. When the structure is subjected to the TCU065 record of the Chi-Chi earthquake, the peak value of BD is obtained about 0.51 m and the peak values of TFAs are obtained as 4.4, 4.0, and 4.1 m/s^2 from SAP2000, 3D-BASIS, and OpenSees, respectively. Time variation of BDs and TFAs under TCU065 record are presented in Fig. 5b and 5d, respectively. It is observed that the time history results obtained from all three programs are in good agreement.

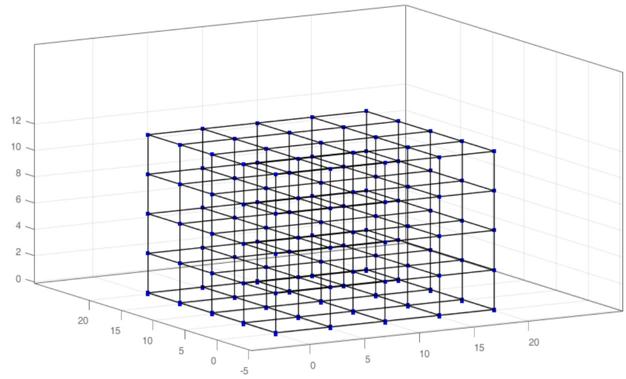

Figure 4. Three-dimensional model of the structure in OpenSees Navigator.

E. Analysis Results of Nonlinear Isolation System with Lead Core Heating Effects

Due to the inability of modeling the effects of lead core heating in SAP2000 and 3D-BASIS, the deteriorating force-deformation relation i.e. the strength deterioration due to heating of the lead core is modeled in OpenSees, only and the extent of the influence of lead core heating is examined via this program. The four-story reinforced concrete base-isolated building described in Section II-A is modeled with designed bearing (see Table I) and nonlinear time history analyses are conducted using Izmit and TCU065 records in OpenSees. Time variation of BDs for both deteriorating and non-deteriorating models are presented in Fig. 5 and associated lead core temperature rise histories are presented in Fig. 6. According to the BD response for Izmit record, which is presented in Fig. 5a, the effect of lead core heating seems to be very low. The peak BDs of both deteriorating and non-deteriorating cases are about 0.11m and the difference between these cases is less than 1 %. On the other hand, for TCU065 record, the peak BD of deteriorating case is 0.58 m, while the peak BD of non-deteriorating case is 0.51 m. The difference between these cases is about 14 %. The reason for this difference can clearly be seen in temperature rise histories presented in Fig. 6. The total amounts of temperature rises in lead cores of LRBs are 10.7 ℃ and 164.2 ℃ for Izmit and TCU065 records, respectively. It can be seen in Fig 5b that the difference between deteriorating and non-deteriorating cases increases after fifty seconds under TCU065 record. The reason is that the temperature rise reaches 114 ℃ in fiftieth second and the corresponding strength deterioration calculated by (6)-(9) reaches 54%. This shows that the differentiation in between cases where the temperature-dependent behavior of LRBs is considered and not considered is a function of the amplitude of the deformation that the bearing undergoes.

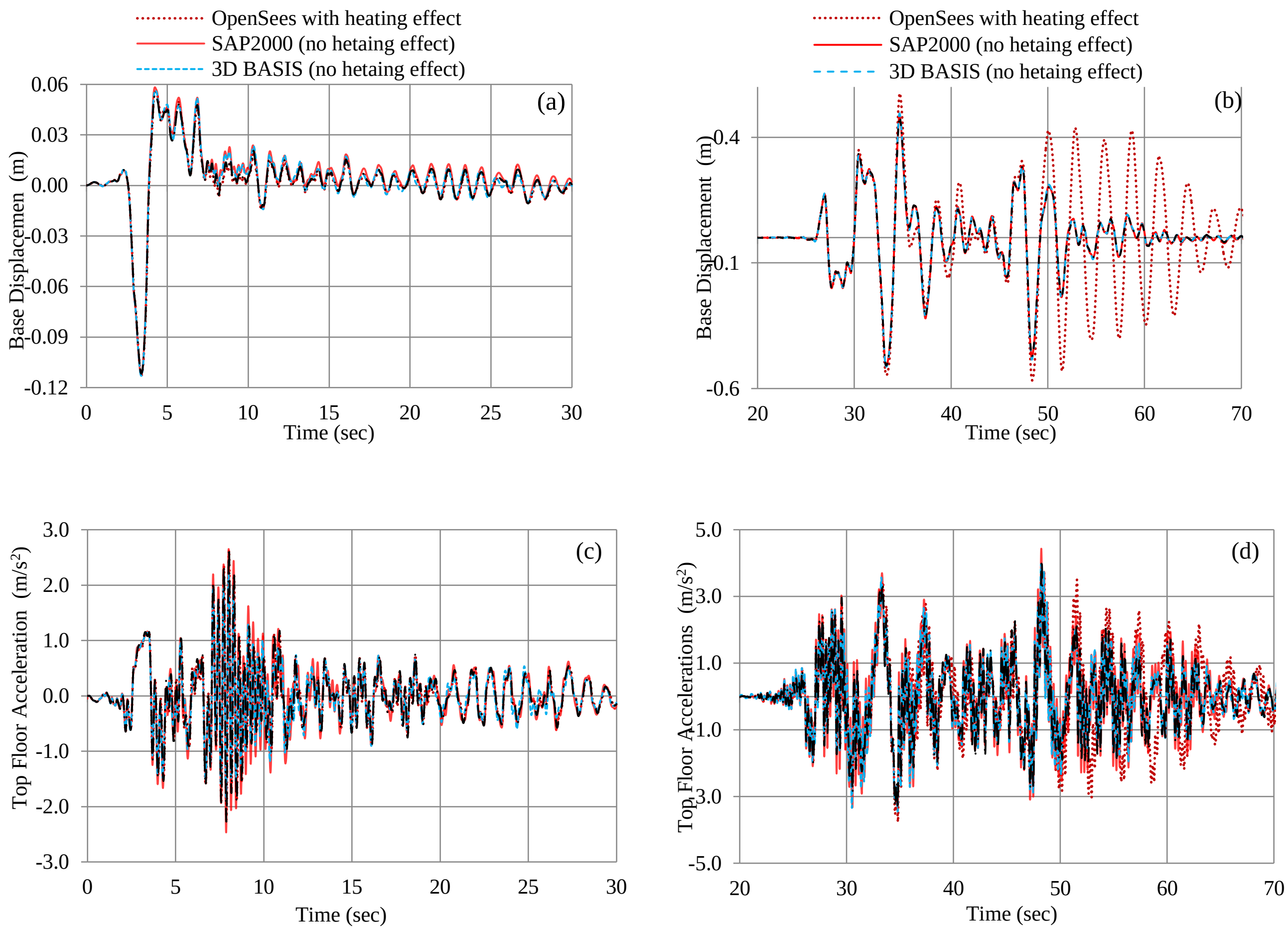

Figure 5. Response time histories of the structure with nonlinear isolation system under (a) and (c) Izmit record, (b) and (d) TCU065 record.

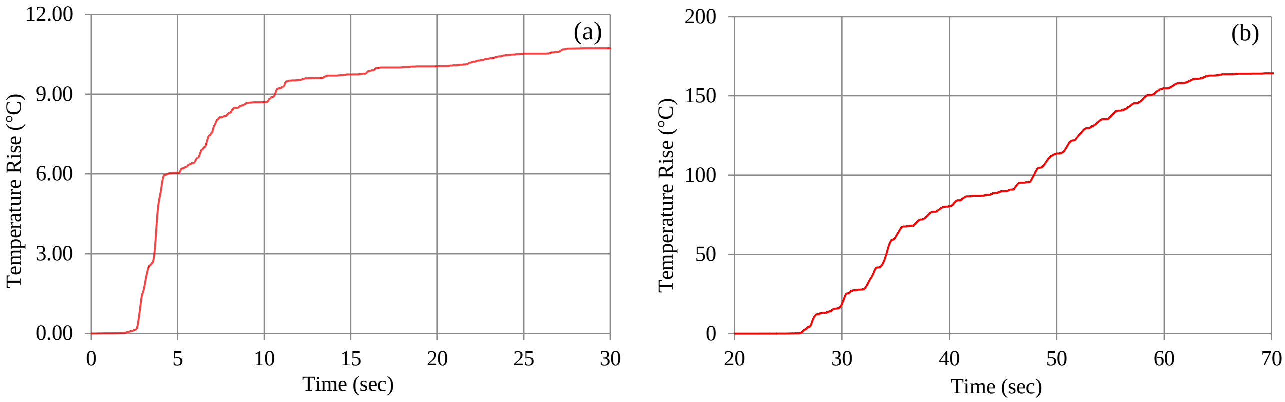

Figure 6. Temperature rise in the lead core of LRBs. (a) Izmit record, (b) TCU065 record.

IV. Modeling and Analysis of Linear Isolation Systems

A. Equivalent Linearization of Isolation System

Although the force-deformation relation of LRBs is nonlinear, the equivalent linear models can be utilized in linear seismic analysis methods by making use of effective stiffness and effective damping. Effective stiffness is obtained assuming a representative linear system having the same maximum displacement as the nonlinear system and effective damping is calculated using the area of the force-deformation hysteretic curve at this displacement [17], [18]. To model the isolation system as an equivalent linear one, it is first necessary to obtain the equivalent linear properties; effective stiffness, K_{eff} and effective damping ratio, β_{eff}. Formulation for these are given by Naeim and Kelly [1] as;

$$K_{\text{eff}} = K_{\text{D}} + \frac{Q}{D} \tag{10}$$

$$\beta_{\text{eff}} = \frac{4Q(D - D_{\text{y}})}{2\pi K_{\text{eff}} D^2} \tag{11}$$

Where Q is the characteristic strength of the isolation system, K_D is the post-elastic stiffness of the isolation system, and D is the peak displacement of the isolation system which is found as 0.11 m and 0.51 m from the time history analysis of nonlinear isolation systems with Izmit and TCU065 records, respectively. By using above equations; K_{eff} is obtained as 20038.45 kN/m and 12163.40 kN/m and β_{eff} is obtained as 0.283 and 0.111 for Izmit and TCU065 records, respectively. Accordingly, the effective period, T_{eff} is calculated as 1.99 and 2.55 seconds via

$$T_{eff} = \sqrt{\frac{M}{K_{eff}}} \tag{12}$$

Where M is the total seismic mass of the structure. It should be noted that the effect of lead core heating cannot be taken into account in linear isolation systems.

B. Modeling via 3D-BASIS

In order to model the isolation system linearly in 3D-BASIS program, effective stiffness of each isolator, k_{eff}, can be input separately. There are two options to define the effective damping. The damping coefficient of the entire system, C_{eff}, can be input to the global damping data section or the damping coefficient of each isolator, c_{eff}, can be defined separately where $k_{eff} = K_{eff} / n$ and $c_{eff} = C_{eff} / n$ with $n = 25$ being the number of isolators in this study. Since all isolators are identical in this study, the damping coefficient of the entire system is defined in the global damping section. The effective damping coefficient is calculated with the following equation, depending on β_{eff};

$$C_{\text{eff}} = 2\beta_{\text{eff}} M \omega_{\text{eff}} \tag{13}$$

where $\omega_{eff} = 2\pi / T_{eff}$.

C. Modeling via SAP2000

One of the options of linear link/support or rubber isolator can be used to create a linear isolator in SAP2000 program. If the rubber isolator element is used, the nonlinear option should not be marked. In both cases, the values of k_{eff} and c_{eff} are defined for each isolator separately.

Here, the linear link/support element, which is fixed in axial direction, is assigned. Similar to nonlinear model, modal damping is used for the superstructure.

D. Modeling via OpenSees

OpenSees does not consist of a special element for linear isolator. Therefore, two node link element is used to construct linear isolator element. This element can be defined by two nodes and six degrees of freedom and the behavior of each degree of freedom is defined by a previously-defined uniaxial material model. A material with previously calculated k_{eff} and c_{eff} values is used for two shear directions, whereas for other degrees of freedom a rather rigid material is used in this study.

E. Analysis Results of Linear Isolation System

The benchmark building described in section II-A is modeled using equivalent linear isolators and time history analyses are conducted using Izmit record of the Kocaeli earthquake and TCU065 record of the Chi-chi earthquake described in section II-C. According to response quantities obtained from time history analyses with Izmit record given in Fig. 7a and 7c; the peak BDs are found as 0.11 m and the peak TFAs are found as 1.6 m/s^2. The peak values

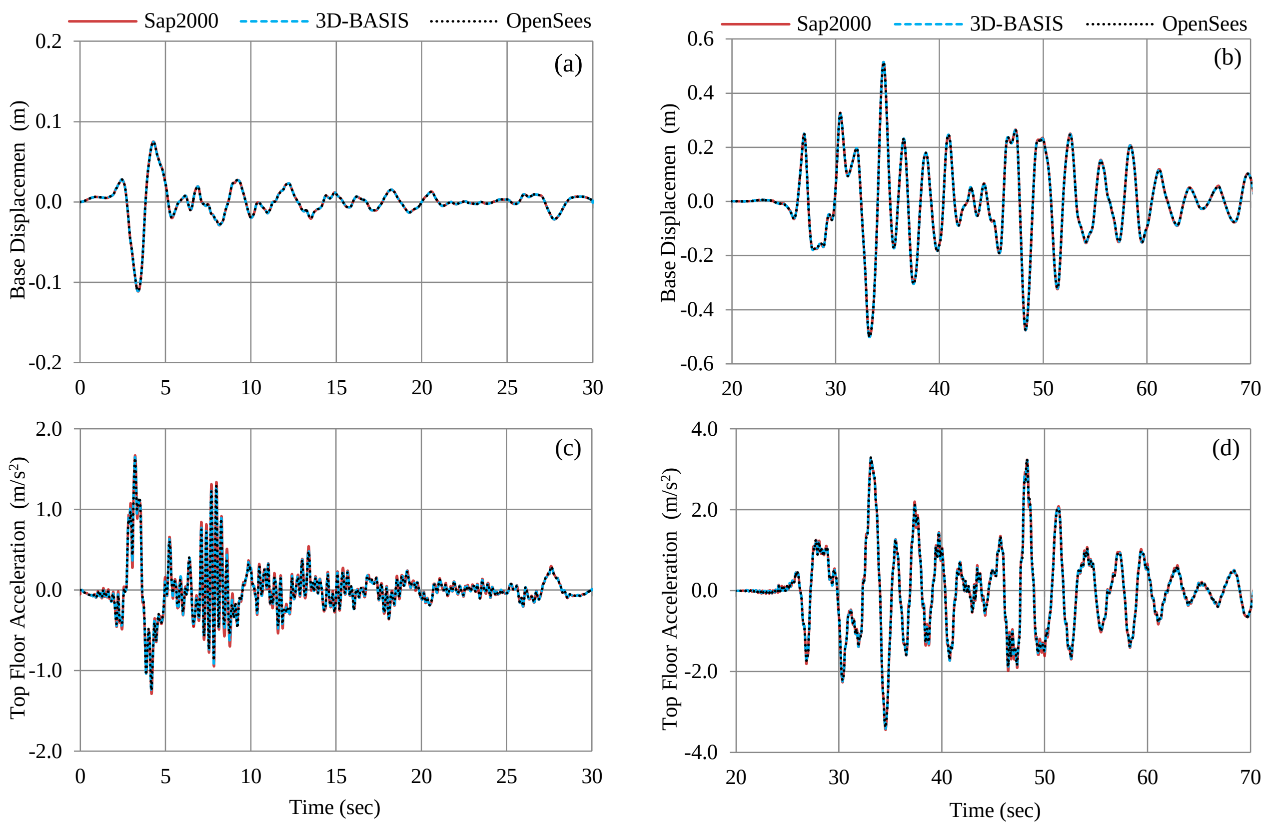

Figure 7. Response time histories of the structure with linear isolation system. (a) Izmit record, (b) TCU065 record

obtained with all three programs are found to be very close to each other. For TCU065 record of the Chi-Chi earthquake, the peak BDs are about 0.51 m and the peak values of TFAs are about 3.4 m/s^2. Time variation of the BDs and TFAs for TCU065 record are presented in Figure 7b and 7d, respectively. As seen from the time histories, all three programs closely match each other throughout the whole time history for both earthquake records.

V. Conclusions

In this study, modeling and analysis of base-isolated buildings with linear and nonlinear isolation systems in three different computer programs, namely SAP2000, 3D-BASIS, and OpenSees are comparatively presented in the context of a generic low-rise base-isolated frame type reinforced concrete building. Structural responses are obtained by performing time history analyses under Izmit and TCU065 records representing low and large level ground motions, respectively. The following are the conclusions reached and the points that deserve to be highlighted:

- Heating of lead core cannot be taken into account in case of linear isolation systems.
- There exists no significant difference between the analysis results obtained from SAP2000, 3DBASIS, and OpenSees in case of linear isolation systems.
- Of the programs studied herein, the extent of the influence of lead core heating could be examined with OpenSees, only, because of the inability of SAP2000 and 3DBASIS in capturing the associated strength deterioration.
- In case of nonlinear isolation systems, there exists no significant difference between the analysis results obtained from SAP2000, 3D-BASIS, and OpenSees - with no heating effect.
- The differentiation in between cases where the temperature-dependent behavior of LRBs is considered and not considered is a function of the amplitude of the deformation that the bearing undergoes.

Acknowledgment

The authors would like to thank the Faculty Member Training Program Office (OYP) of Istanbul University for providing financial support.

References

[1] F. Naeim and J. M. Kelly, *Design of Seismic Isolated Structures*, New York: Wiley, 1999, ch. 1.

[2] W. H. Robinson, “Lead-rubber hysteretic bearings suitable for protecting structures during earthquakes,” *Earthquake Engineering and Structural Dynamics*, vol. 10, pp. 593-604, July/Aug. 1982.

[3] I. V. Kalpakidis and M. C.Constantinou, “Effects of heating on the behavior of lead-rubber bearing. I: Theory,” *Journal of Structural Engineering (ASCE)*, vol. 135, no. 12, pp. 1440-1449, Dec. 2009.

[4] I. V. Kalpakidis and M. C.Constantinou, "Effects of heating on the behavior of lead-rubber bearing. II: Verification of Theory," *Journal of Structural Engineering (ASCE)*, vol. 135, no. 12, pp. 1450-1461, Dec. 2009.

[5] S. Arguc, O. Avsar, and G. Ozdemir. (October 2017). Effects of lead core heating on the superstructure response of isolated buildings. *Journal of Structural Engineering (ASCE)* [Online]. 143(10). pp. 04017145/1-15. Available: https://doi.org/10.1061/(ASCE) ST.1943-541X.0001880

[6] SAP 2000, "Integrated software for structural analysis and design," *Computers and Structures Inc*., Version 19.2.0, Berkeley, C A, 2017.

[7] S. Nagarajaiah, A. M. Reinhorn, and M. C. Constantinou, *3D-BASIS: "Nonlinear Dynamic Analysis Of Three-Dimensional Base Isolated Structures: Part II*," Technical Report NCEER-91-0005, National center for earthquake engineering research, State University of New York at Buffalo, 1991.

[8] Open Sees, "Open System for Earthquake Engineering Simulation,".F. McKenna, G. Fenves, and M. Scott. (2006). Pacific Earthquake Engineering Research Center, University of California, Berkeley, CA, (http://opensees.berkeley.edu).

[9] Z. Kanbir, "Effect of lead core heating on the behavior of seismically isolated structures," Ph.D. dissertation, Dept. Civil Eng., Istanbul Univ., Istanbul, Turkey, (unpublished).

[10] C. Alhan and M. Sürmeli. (June 2011). Shear building representations of seismically isolated buildings. *Bull Earthquake Eng* [Online] 9. pp. 1643-1671. Available: https://doi.org/10.1007/s10518-011-9293-z

[11] M. C. Constantinou, A. S. Whittaker, D. M. Fenz, and G. Apostolakis, *Seismic Isolation of Bridges,* New York, Report Submitted to the State of California Department of Transportation, University at Buffalo, Version 2, June 2007.

[12] PEER, 2013, Pacific Earthquake Engineering Research Center Ground Motion Database, University of California, Berkeley, CA, (http://ngawest2.berkeley.edu)

[13] P. C. Tsopelas, S. Nagarajaiah, M. C. Constantinou, and A. M. Reinhorn, *3D-BASIS-M:" Nonlinear Dynamic Analysis Of Multiple Building Base Isolated Structures,"* Technical Report NCEER-91-0014, National center for earthquake engineering research, State University of New York at Buffalo.1991.

[14] M. Kumar, *Computer Program ElastomericX, LeadRubberX, and HDR: User elements in OpenSees for analysis of elastomeric seismic isolation bearings under extreme loading*, OpenSees, Buffalo, NY, 2014, http://opensees.berkeley.edu/wiki/index.php

[15] MATLAB Runtime 9.1 (R2016b), The MathWorks, Inc., Natick, Massachusetts, United States, 2016. https://www.mathworks.com/ products/compiler/matlab-runtime.html

[16] OpenSees Navigator, "MATLAB based graphical user interface" A. Schellenberg, T. Yang and E. Kohama, Pacific Earthquake Engineering Research Center, Berkeley, CA, Release 2.5.7, 2016 (http://openseesnavigator.berkeley.edu)

[17] C. Alhan and M. Ozgur, "Seismic responses of base-isolated buildings: efficacy of equivalent linear modeling under near-fault earthquakes," *Smart Struct. Syst*., vol. 15, no. 6, pp. 1439-1461. June 2015.

[18] G. Ozdemir, "Formulations of equivalent linearization of lead-rubber bearings for incorporating the effect of lead core heating," *Earthquake Spectra*, vol. 31, no. 1, pp. 317-337. February 2015.

Zafer Kanbir has completed his BS and MS degrees in Civil Engineering at Yildiz Technical University and Istanbul Technical University in 2007 and 2012, respectively. He worked as a research assistant at Isik and Kirklareli Universities in 2014–2016. In 2016, Kanbir has started working as a research assistant in structural engineering division at Istanbul University where he is currently a PhD candidate. His major field of study is structural and earthquake engineering with emphasis on nonlinear seismic analysis and seismic isolation.

Gökhan Özdemir received a BS degree (2002) from Civil Engineering Department of Gazi University, the degrees of MS (2005) and PhD (2010) from Civil Engineering Department of Middle East Technical University. He has been working at Anadolu University of Eskişehir, Turkey as a faculty member since 2013. Prof. Özdemir's current research interest is mostly on the design of seismically isolated structures and specifically, the change in nonlinear response of both isolator units and superstructures due to variation in hysteretic behavior of isolator units. He has published several articles in well-respected journals including, but not limited to, Earthquake Spectra, Earthquake Engineering and Structural Dynamics. Prof. Özdemir also served as a reviewer in these archival journals.

Cenk Alhan has earned his BS, MS, and PhD degrees in civil engineering at Middle East Technical University (Turkey), Bogazici University (Turkey), and Duke University (USA) in 1996, 1999, and 2003, respectively. He worked as a research assistant at Bogazici and Duke Universities in 1997–2000 and 2000–2003, respectively. During his stay at Duke, he worked as a researcher in a National Science Foundation funded research project. He became a Faculty Member at Istanbul University in 2006 where he currently works as a Professor in Civil Engineering Department. He works in structural and earthquake engineering area and his research interests include probabilistic structural dynamics, seismic isolation, semi-active control, irregular structures, strengthening, and engineering education. He teaches Courses in structural and earthquake engineering including Statics, Strength, Structural Mechanics, Structural Analysis, Earthquake Engineering, Seismic Isolation, and Structural Dynamics. He has given oral presentations at conferences and seminars worldwide such as those in Boston, Alaska, Edmonton, Michigan, Vienna, Istanbul, Singapore, Sydney, Delft, Barcelona, and Reykjavik. Prof. Dr. Cenk Alhan has published in important technical journals including Journal of Structural Engineering, Journal of Engineering Mechanics, Smart Materials and Structures, Engineering Structures, Engineering Optimization, Mechanical Systems and Signal Processing, Earthquake Engineering and Engineering Vibration, Smart Structures and Systems, and Bulletin of Earthquake Engineering for which he has received more than a hundred citations. He also acts as a Reviewer for various SCI journals.