# EFFECTS OF THE MECHANICAL CHARACTERISTICS OF LRB'S ON STRUCTURAL RESPONSE OF BASE ISOLATED BUILDINGS

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**ABSTRACT :**

This study examines parametrically the response of a seismic isolated multistory-structure. The characteristics of the isolation system are based on the analytical investigation and results from a dynamic thermo mechanical analysis (TMC) of a characteristic Lead Rubber Bearing (LRB). The parametric analyses of the structure are based on seismic records and provisions for seismic isolation.
For the aforementioned structure, nonlinear dynamic history analyses are performed using three accelerograms in order to have a more accurate picture of the contribution of the base isolation system to the total seismic forces that are developed at the superstructure during seismic excitations. It must be noted that the response of the superstructure is considered to be elastic, while the response of the seismic isolation bearings is inelastic. For the time-history analysis the model is subjected to three scaled seismic excitations, given by the horizontal accelerograms of El Centro, Kalamata and Thessaloniki earthquakes. Furthermore, an iterative process has been adopted to design the bearings according to code provisions and researches on seismic isolation of structures.
The aim of these parametric analyses is to investigate the influence of the LRB mechanical characteristics in the superstructure response. More specifically, the superstructure response is examined for the expected variations of the lead's yield stress values. These variations are related to the temperature that is developed in the lead core of the LRB, due to the convertion of plastic work into heat by the seismic excitations.

**KEYWORDS:** Base isolation, Lead Rubber Bearing, Dynamic Thermo Mechanical analysis.

## 1. INTRODUCTION

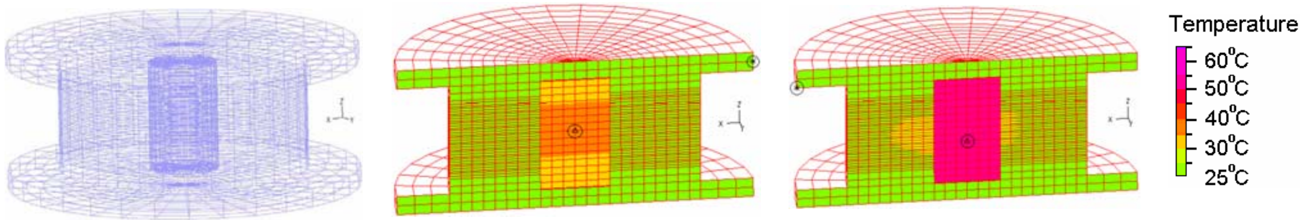
The earthquakes of the last decades all over the world, as well as the recent earthquakes in Greece, have caused the major social and financial issue of seismic behavior and, in general, the resistance of structures to earthquake forces to became a mater of high priority. Several methods have been developed in order to improve the structure's response in earthquake movements, due to this necessity to confine the earthquakes' consequences [1, 2].

A major field of these developments is related to seismic isolation in the base of structures, which is considered to be a mature technology that has been used and tested in many countries [3]. For the implementation of seismic isolation, the building's superstructure is separated from the foundation through the placement of specific components (isolation bearings). These bearings have a high vertical but low horizontal stiffness, resulting in a significant reduction of the seismic accelerations that are transmitted to the superstructure. This reduction is achieved by several ways, including the elongation of the dominant period of the structure. In this case, there are significant reductions of accelerations as well as of the interstory drifts of the superstructure, although the elongation of the period results in increased displacements in comparison to buildings with a conventional foundation [4]. The intense research activity in the field of seismic isolation has led to the development of a variety of isolation bearings, which have been tested by many countries with very encouraging results. Characteristically, we could report that the most common types of seismic isolation are the elastomeric and the sliding bearings. The elastomeric bearings consist of consecutive layers of rubber and stainless steel with a lead core (LRB) or without one (DRB). The sliding systems are either of a flat (Friction Base Isolation System) or a curved form (Friction Pendulum System) and consist of interfaces of suitable plastic material and stainless steel. It is also important not only to develop simpler seismic isolation systems but also to evaluate the behavior of the bearings in real circumstances [5]. Researches in the evolution of the analytical micro models [6, 7] of the seismic isolation systems also contribute to the completeness of this attempt, in order to include more realistic data of their behavior.

This paper is part of the general progress that has been made in the field of seismic isolation of structures. It presents the parametric examination of a multi-storey building's response with elastomeric bearings with a lead core. Granted that the programs available are not able to make a thermo mechanical analysis of the bearings in the whole model of the structure, a certain calculation process is proposed, based on the seismic records and Building Codes [8, 9, 10] and the results from a dynamic thermo mechanical analysis of micromodel bearings [7]. The results of the micromodel's analyses (Figure 1), which verify previous outline observations [6, 11], are elaborated in this paper and present with accuracy the bearing's (LRB) behavior during each time step of the seismic excitation. The thermo mechanical analysis of the micromodel leads to the following conclusions:

- The change of the lead's properties can now be calculated with accuracy, as well as the mechanical properties and temperature of the bearing for each time step of the seismic excitation.
- The percentage of the plastic work, which turns into heat inside the lead core, reaches approximately 60%.
- The loading rate, as a factor of the temperature change, influences the behavior of the bearing.

In the current study, nonlinear time-history analyses are performed, taking into account the appropriately calculated expected variations of the bearings' force-displacement (hysteretic) loop, due to the rise of the temperature of the lead core. In that way, the envelope of the structure displacements as well as the stress values of its elements can be obtained by the analyses' results, so as to design it in a secure way. For these analyses, the horizontal accelerograms of Kalamata, El Centro and Thessaloniki earthquakes have been used.




(a) (b) (c)

Figure 1 The form of the micromodel which has been used for the thermo mechanical analysis (a) and (b, c) the change of the temperature in various time steps of the analysis.

It should be noted that, in order to define the dimensions of the bearings, an iterative process has been performed according to the provisions and publications that are related to the seismic isolation of the structures [3, 12]. The final records and the dimensions of the bearings come out after being tested in an earthquake. This is achieved by the inelastic time history analysis and an approximate approach of the desirable values of the dominant period and the structure's displacement.

After the confirmation of the changes that the properties of the elastomeric bearings with a lead core have been imposed, additional non-linear dynamic analyses are performed, so as to examine the changes of the superstructure's response. In particular, the changes of the superstructure's response are being examined in relation to the expected changes of the bearing properties, due to the temperature change in the lead core. This change is not stable but it varies in each time step during the seismic excitation.

The objective of this study is to 'estimate' the expected variations of the analyses of the results in relation to the expected variation of the bearings' hysteresis loop each time step of the seismic excitation. Also, it is intended to define the structure's displacements and the stress envelope, so as to achieve a secure design of the building.

## 2. THE BUILDING'S DESCRIPTION

The following analytical comparative parametric study is applied to a six-storey reinforced concrete building, the plan and elevation of which can be seen in Figure 2. The building consists of an exterior space frame with 6 columns and 4 walls, together with 2 isolated interior columns, which are connected to the exterior frame with floor stabs. The additional permanent load of slabs is g=1.2 kN/m$^2$, while the live load is q=5.0 kN/m$^2$.

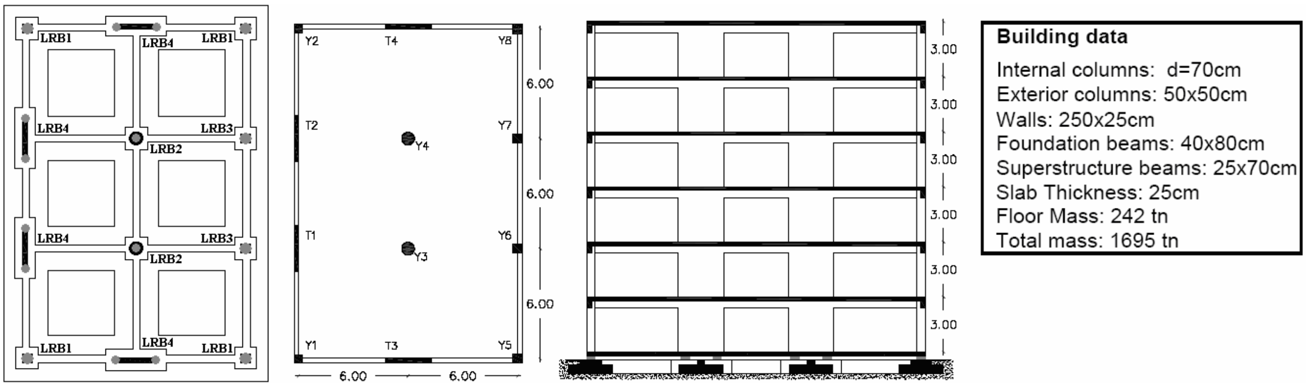



Figure 2 Plan view (foundation and superstructure) and elevation view of the building.

The special configurations in the structure, due to seismic isolation implementation are the following:

- The building's foundation on the natural ground consists of a grillage of footing and beams, which is connected with the superstructure through the seismic isolation bearings.
- An additional grillage of tie beams is created on the base of the superstructure, which are connected with each other through a reinforced concrete slab-diaphragm that constitutes also the first floor storey.
- The bearings are positioned at the bottom of each column and at the ends of the walls (Figure 1).
- The gap around the perimeter of the first storey, just above the foundation, is necessary for the building's free sliding during the seismic excitations.

The program SAP2000 is used for the simulation and the analysis of the structure. Linear frame finite elements are used for the beams, columns and walls and the diaphragm function of the slabs in the floors' level is considered. The vertical compressibility of the ground is taken into account with the use of vertical springs. The stiffness of the ground is $K_g$=100000 kN/m$^3$ while the permissible ground stress is 200 kN/m$^2$.

## 3. ANALYSIS METHOD

For the bearings of the structure, elements with non-linear behavior are used. The stiffness of these non-linear elements depends on the imposed loading. For the modeling of the bearings, the element 'isolator1' of the computer program SAP2000 is used [13]. Analytically, we could refer that, throughout the analysis, the element, which represents the elastometalic bearing's behavior, consists of six 'springs'. These are equivalent to the six free movements (axial, vertical, torsion and bending). Each one of these springs has two values of stiffness:

- Linear effective stiffness and effective damping for the linear analysis.
- Non-linear strain-stress relation only during the time-history analysis.

Nonlinear dynamic history analyses are performed, to give a more accurate picture of the contribution of the base isolation system to the total seismic forces that are developed at the superstructure during a seismic excitation. It must be noted here that the response of the superstructure is elastic, while the response of the seismic isolation bearings is inelastic. For these analyses, the model was subjected to 3 scaled excitations, given by the horizontal accelerograms of El Centro, Kalamata and Thessaloniki earthquakes. The scaling factors are based on Housner's normalization for a probability of exceedance of 10% in 50 years and 10% in 100 years.

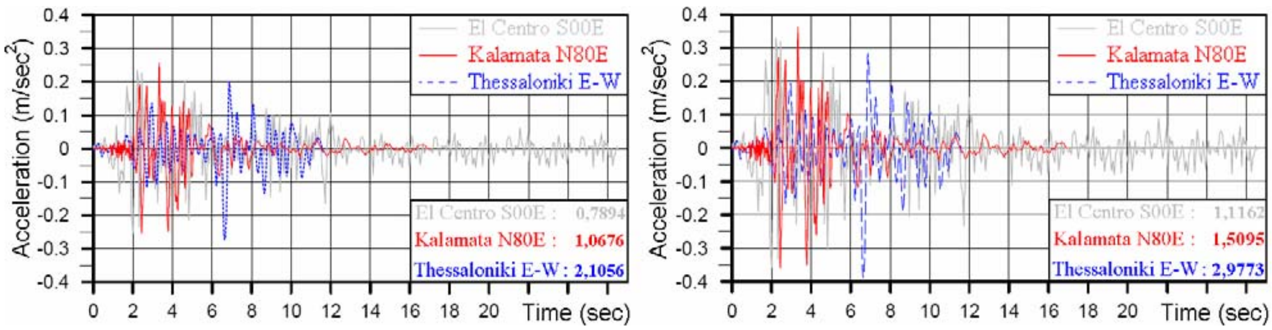



Figure 3 Scaled earthquakes motions with exceedance probability: 10% in 50 years (left) and 100 years (right).

All the results that are presented below were developed from the loading of the structure initially with the seismic combination of the gravity loading G+0.3Q and afterwards with the simultaneous seismic excitation (accelerograms) to directions x and y.

### *3.1. Specification of the targeted displacement and the dominant period*

For the above mention building the behavior coefficient is 1.5 according to building regulations UBC and EC8. The acceleration (according to Greek Seismic Code for seismic zone III) is A=0.36 and we want it to be reduced to 0.36/1.5=0.24.

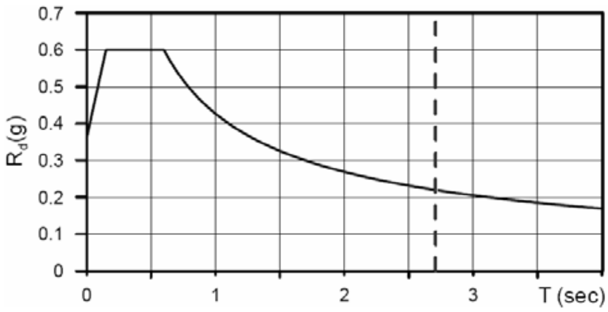


Figure 4 Spectrum acceleration according to Greek Seismic Code, for A=0,36g and q=1.5.

So, the targeted displacement and dominant period are:

i. Targeted dominant period: the seismic isolated building has a longer dominant period, therefore we ¨move¨ to the third phase of the spectrum of G.S.C. (figure 4).

$$\mathrm{R_e(T)} = \mathrm{A}\cdot\gamma_\mathrm{I}\cdot\eta\cdot\beta_o\cdot\frac{T_2}{T} \Rightarrow 0{,}36\cdot 1\cdot 0{,}76\cdot 2{,}5\cdot\frac{0{,}60}{T} = 0{,}24 \Rightarrow T = 2{,}73\,\mathrm{sec} \quad (3.1)$$

Where: $\gamma_I$, $\eta$ and $\beta_o$ are the importance, the corrective (0.76 for 10% damping) and the increase coefficients.

ii. Targeted displacement:

$$D_D = \frac{g}{4\pi^2}\cdot\frac{S_X\cdot T_D}{B_D} \Rightarrow D_D = \frac{9{,}81}{4\cdot\pi^2}\cdot\frac{0{,}56\cdot 2{,}73}{1{,}5} \Rightarrow D_D = 0{,}25\ \mathrm{m} \quad (3.2)$$

Where: $S_X$ is the Spectral response acceleration parameter, $T_D$ is the period and $B_D$ is the damping coefficient.

### *3.2. Dimensioning of the bearings.*

The first estimation of the dimensions and the properties of the bearings is based on the regulations of UBC, of FEMA and of J. Kelly and F. Naeim's proposals. The basic principle for this estimation is the analysis of the structure's model with fixed base for the G+Q combination, so that the load of each bearing can be estimated.
It should be noted that the bearings dimensions are estimated using an iterative inelastic time history analysis in order to achieve the desirable values for the period and displacement of the structure (Table 1).

Table1: The dimensions and the characteristics of the bearings after successive approaches are:

| Column (Bearing) | $D_{tot}$ (m) | $D_{pd}$ (m) | $K_{eff}$ (KN/m) | $K_I$ (KN/m) | Qy (KN) | $W_D$ (KN) | $\beta_{eff}$ |
|---|---|---|---|---|---|---|---|
| $Y_1$, $Y_2$, $Y_5$, $Y_8$ | 0,40 | 0,07 | 636,34 | 4105,43 | 44,04 | 33,35 | 0,17 |
| $Y_3$, $Y_4$ (LRB2) | 0,70 | 0,12 | 1938,61 | 12681,98 | 129,43 | 98,23 | 0,16 |
| $Y_6$, $Y_7$ (LRB3) | 0,50 | 0,095 | 1018,92 | 6183,60 | 81,12 | 60,80 | 0,19 |
| $T_1$, $T_2$, $T_3$, $T_2$ (LRB4) | 0,55 | 0,10 | 1215,94 | 7634,07 | 89,88 | 67,76 | 0,18 |

## 4. THE HYSTERESIS LOOP OF THE BEARING AND THE TEMPERATURE OF THE LEAD CORE

In this part, the evaluation of the hysteresis loops is being processed as well as the specification of the temperature change for the bearing with a lead core, which has been chosen for the seismic isolation base of the particular building. This specification is based on the observations of experimental labs [6], where it has been ascertained that the decrease of the bearings' loop with a lead core is mainly due to the temperature developed in the bearing and specifically in the lead part during its plastic deformation (energy absorption of the earthquake). So, according to the above findings as well as the approximated calculation of the developed temperature [8, 12], the change of the temperature in the lead core of the LRB bearings is defined by:

$$T(t) = \frac{1}{\rho \cdot c \cdot V} \cdot \int_{0}^{u(t)} \mathrm{F} \cdot \mathrm{du} \qquad (4.1)$$

Where: V is the volume of the lead core, F is the shear force of the bearing, u is the displacement of the bearing, ρ and c, the density and special temperature of the lead.

This value represents the rise of the temperature for the total of the loading circles, as a result of the earthquake movement. So, if we take into consideration that the initial value of the environmental temperature is 25$^{o}$C, then, the value of the temperature of the lead core of the bearing is 25$^{o}$C+T(t), after the passing of the earthquake. According to the above and changes of the lead's mechanical properties (figure 5), it is necessary to redefine the bearings' characteristics that are used in the seismic isolation of the structure.

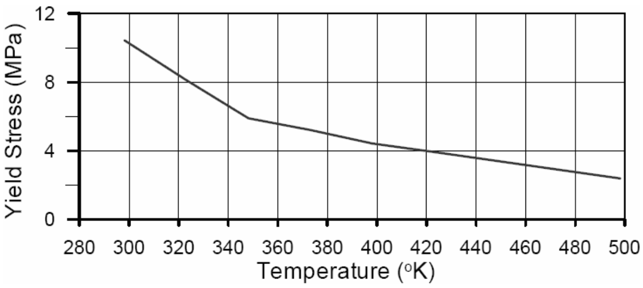



Figure 5 The change of stress leakage of the lead core for different temperatures.

For the analytical calculation of the rise of the temperature we should:

i. Define the volume of the lead core for each bearing, as well as the density and the special temperature of the lead (table 2).
ii. Define the energy dissipated by each bearing. The base of this calculation are the hysteresis loops of the bearings, during the seismic movements (table 2).

For this evaluation the loops created by the earthquake of El Centro have been used (figure 6).

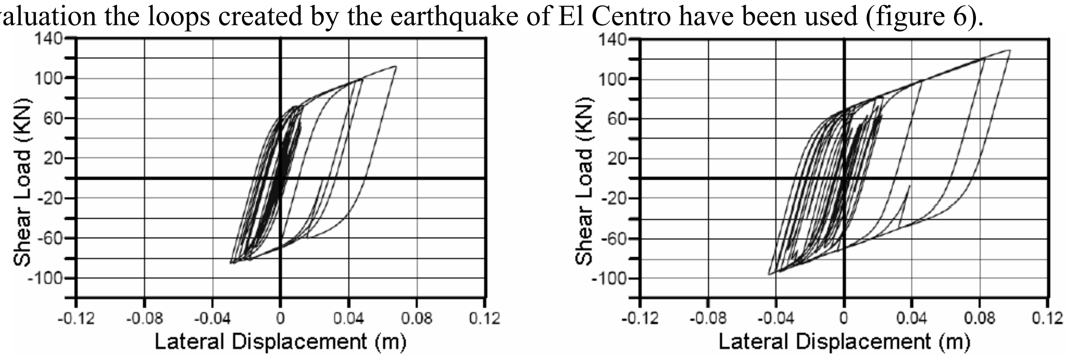



Figure 6 The hysteresis loops of LRB2 bearing for the El Centro earthquake with probability of exceedance of 10% in 50 years (left) and 10% in 100 years (right).

After the calculation of the dissipated energy, the rise of the temperature in the core of the bearings follows, as presented in table 2. There, it is certified that the highest rise is observed for the bearing LRB1 wile the lowest is observed for the bearing LRB2 in both occasions of the probability of exceedance.

Table 2: The dimensions and the mechanical characteristics of the lead core of the bearings used and the change of their temperature, for the earthquake of El Centro with probability of exceedance of 10% in 100 years.

| | LRB1 | LRB2 | LRB3 | LRB4 | |
|---|---|---|---|---|---|
| $D_{TOT}$ (m) | 0,400 | 0,70 | 0,50 | 0,55 | |
| Dpd (m) | 0,07 | 0,12 | 0,095 | 0,10 | |
| Apd ($m^2$) | 0,004 | 0,011 | 0,007 | 0,008 | |
| Vpd ($m^3$) | 6,927E-04 | 2,036E-03 | 1,276E-03 | 1,414E-03 | |
| ρ c ($KN/m^{2o}C$) | 1,463E+03 | 1,463E+03 | 1,463E+03 | 1,463E+03 | |
| $W_{Dtot}$ (KNm) | 82,37 | 84,90 | 85,00 | 84,67 | 10% in 100 years |
| $T_{tot}$ (°C) | 81,29° | 28,51° | 45,54° | 40,94° | |

The results of the table above show characteristically that the rises of the temperature of the bearings' lead core do not coincide in any time step even for the bearings with minor differences in shape and size. This is an important element for the design and the expected values of response in the base of seismic isolated buildings. Taking into account, now, the new data and the shape of figure 5, where the range of values of lead's stress tendency is presented, we can define the new values of the lead's stress tendency:

Consequently, it is obvious that this change will affect essential elements for the analysis of the structure, concerning the bearings used. These changes of the bearings' characteristics are presented in table 3.

Table 3: The change of the bearings' characteristics, altered due to temperature rise for the El Centro earthquake for a probability of exceedance of 10% in 100 years.

| Columns | $K_{eff}$ (KN/m) | $K_1$ (KN/m) | Qy (KN) | $W_D$ (KN) | $\beta_{eff}$ |
|---|---|---|---|---|---|
| $Y_1$, $Y_2$, $Y_5$, $Y_8$ (LRB1) | 557,62 | 4105,43 | 24,80 | 19,16 | 0,11 |
| $Y_3$, $Y_4$ (LRB2) | 1707,27 | 12681,98 | 72,88 | 56,37 | 0,11 |
| $Y_6$, $Y_7$ (LRB3) | 873,94 | 6183,60 | 45,68 | 35,08 | 0,13 |
| $T_1$, $T_2$, $T_3$, $T_2$ (LRB4) | 1055,29 | 7634,07 | 50,61 | 39,00 | 0,12 |

After the modifications of the elements of the bearings and the performance of the analysis of the El Centro earthquake with a probability of exceedance of 10% in 50 years, the following loops come up (figure 7).

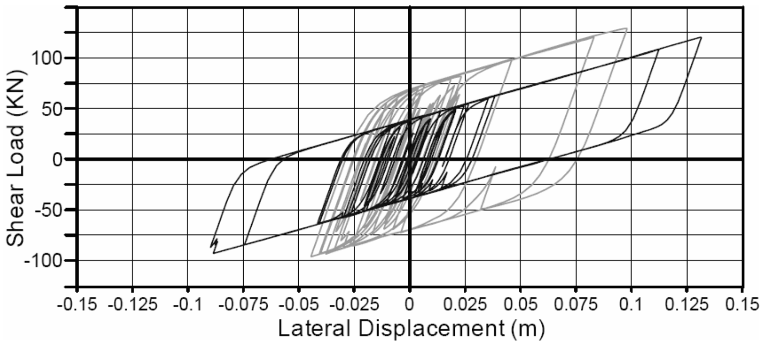



Figure 7 The hysteresis loops of LRB2 bearing for the El Centro earthquake with probability of exceedance of 10% in 100 years, before (gray) and after (black) the characteristics' change due to temperature rises.

## 5. COMPARATIVE EVALUATION OF THE RESULTS

This part presents some characteristic results of the elements of the structure for different seismic movements that have been examined. All the following diagrams show a comparative evaluation of the structure's behavior, for the initial and modified (due to the change of temperature) properties of the bearings. As an immediate result, which depends on the bearings' stiffness and the size of seismic input, the displacement of the diaphragm over the seismic isolation system could be considered. The following figure (8) presents the displacements for one of the three cases of seismic movements and the two probabilities of exceedance, as UBC-97 defines.

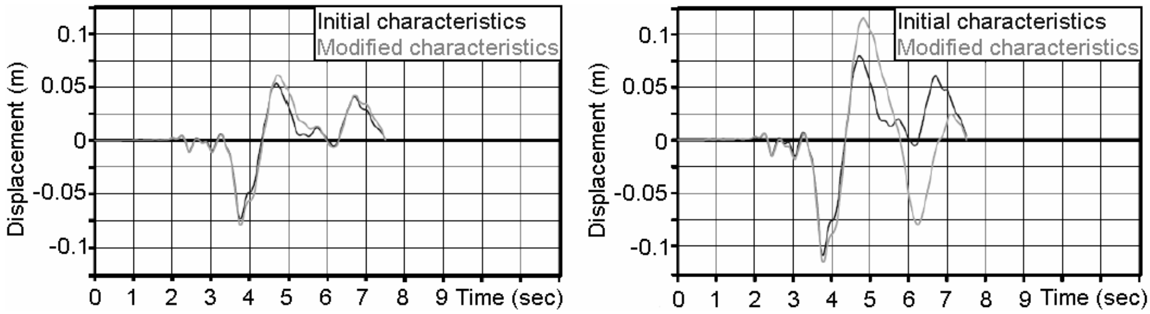



Figure 8. The displacement of the diaphragm over the seismic isolation system for the earthquake of Kalamata with a probability of exceedance of 10% in 50 years (left) and 10% in 100 years (right).

As it has been expected, after the properties' change (decreasing scale) of the bearings, there has been an increase of the diaphragm's movements over the seismic isolation system. The biggest increase is observed for the case of probability of exceedance of 10% in 100 years, when in specific time steps it surpasses 50% of the initial displacement.
The diaphragm's rotation over the seismic isolation system is an important element that needs to be examined, since they affect the whole displacement of the upper slab of all the bearings (with an emphasis on all the end points of the structure's seismic movements). The change of the rotations for all the cases of seismic movements and the probabilities of exceedance is presented in Figure 9.

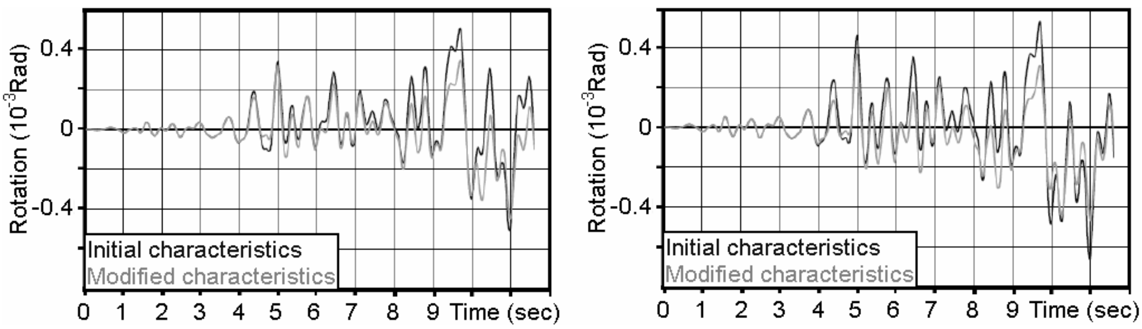



Figure 9. The rotations of the top of the bearing LRB1 of the end column Y8, for the earthquake of Thessaloniki, with a probability of exceedance of 10% in 50 years (left) and 10% in 100 years (right).

Even though the rotations of the diaphragm over the seismic isolation system are small enough, due to the symmetrical shape of the structure, there are changes that could not be overlooked whatsoever.

In figure 10 that follows, the shearing reaction of the bearing LRB2 is presented (of a central column) with the changes of the curve to be representative of all the bearings.

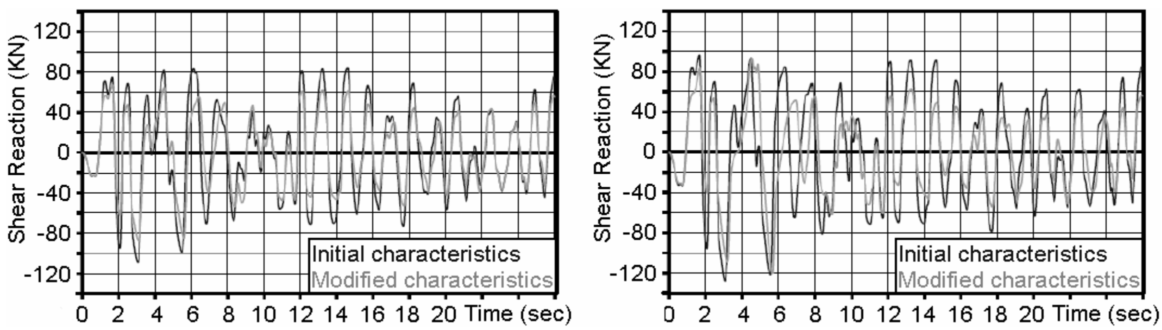



Figure 10. The shear force which develops in the bearing of the column Y4 for the earthquake of El Centro with a probability of exceedance of 10% in 50 years (left) and 10% in 100 years (right).

In the figures above, a general reduction of the shear reaction of the bearing LRB2 from 20% up to 30% for both probabilities of exceedance is observed. For some particular time steps the reduction climb up to 100%.

## 6. CONCLUSIONS

According to what has been mentioned the effect of the temperature rise in the lead core of the LRB bearings, due to plastic deformations during a strong earthquake, has a strong influence on the design of the structure. From the parametric analysis the conclusions are the following:

- The displacements and rotations of the diaphragm over the seismic isolation system and the differential movements of the floors of the structure depend on the bearings' behavior and the frequential content of the earthquake each time step. Due to this fact, we are obliged to take into consideration the rise of the temperature in the lead core and the change of the bearings' characteristics.
- The Elastic Rotation Centre of the bearings, which according to the design rules has to coincide with the superstructure's centre of gravity, is affected mainly by the differential reduction of the characteristics of the bearings, since each one of them develops different temperature. In any case, it is necessary to evaluate the effect of temperature, which develops in the elastomeric bearings with a lead core and this should be taken into account when designing the base isolation system.
- Although the performed analyses show the extreme values for different response quantities and they constitute a secure solution of designing a structure, it is certain that they are not the best solution. Therefore, in order to achieve the best profitable design of the structure, it is necessary to define accurately the change of the bearings' characteristics in relation to all parameters that affect them.

## REFERENCES

1. Naeim F. and Kelly J. M. (1999). Design of Seismic Isolated Structures: From Theory to Practice, John Wiley & Sons
2. Kelly J. M. (1990). Base Isolation: Linear Theory and Design. *Journal of Earthquake Spectra*, **6**, 223-244.
3. Anderson T. L. (1990). Seismic Isolation Design and Construction Practice *Proc. 4th U.S. Nat. Conf. on Earthq. Engrg., Earthq. Engrg. Res. Inst.*, **3**, 519-528.
4. Gravalas F. T., Papadopoulos P. and Doudoumis N. I. (2007). Parametric analysis of a base isolated building's response according to experimental results on mechanical characteristics of sliding isolation systems. *1rs international conference on computational methods in structural dynamics and earthquake engineering.* Rethymno, Crete, Greece.
5. HITEC & CERF. (1999). Summary of Evaluation Findings for the Testing of Seismic Isolation and Energy Dissipating Devices. Highway Innovative Technology Evaluation Center & Civil Engineering Research Foundation. **CERF Report: 40404**.
6. Doudoumis I., Gravalas F., Doudoumis N. (2005). Analytical Modeling of Elastomeric Lead-Rubber Bearing with the use of finite element micromodels. *5th International Congress on Computational Mechanics.* Limassol
7. Gravalas T. Fotios. (2007). A contribution on the research of the mechanical characteristics of base seismic isolation devices and an evaluation of their influence on the response of seismic isolated structures. Ph. D. Thesis, Department of Civil Engineering, Aristotle University of Thessaoniki, Greece.
8. UBC. (1994). Uniform Building Code Appendix Division III Earthquake Regulations for Seismic-Isolated Structures. American Association of Building Officials, Whittier, CA.
9. Federal Emergency Management (FEMA). (1997). NEHRP Commentary on the Guidelines for the Seismic Rehabilitation of Buildings. Building Seismic Safety Council (BSSC): Washington DC, US.
10. Eurocode 8 (2002). Design of structures for earthquake resistance, Part 1: General rules, seismic actions and rules for buildings. Revised Final Project Team Draft, CEN, European Committee for Standardization.
11. Constantinou M. C., Tsopelas P. Kasalanati A. and Wolff D. E. (1999). Property modification factors for seismic isolation bearings. Technical Report **MCEER-99-0012.**
12. S. Nagarajaiah, A. M. Reinhorn, and M. C. Constantinou. (1993). Nonlinear Dynamic Analysis of Three Dimensional Base Isolated Structures. *National Center for Earthquake Engineering Research,* Buffalo, NY.
13. SAP2000 (2004). Linear and nonlinear static and dynamic analysis and design of three dimensional structures. *Computers and Structures Inc.* **V. 9.0.3** Berkeley, USA.
14. Greek Seismic Code (2000). Earthquake resistance design of structures. Earthquake Planning and Protection Organisation, Athens, Greece.