International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13, Number 23 (2018) pp. 16342-16350
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Optimum Performance of Isolation System for Medium Rise Buildings Subject to Long Period Ground Motions

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Abstract

In the existing literature regarding seismic isolation of structures, most of researches are related to short period earthquakes. Due to such a type of earthquake, the maximum isolator design period is at most 4 secs. This study shows that, for long period earthquakes, the optimum isolator period should be set higher than 4 secs for medium rise buildings. The study compares structural responses in terms of both floors accelerations and displacements for five storeys building isolated by lead core rubber bearing (LCRB). This building is to be located in area with long period ground motion characteristics. Its responses are computed through numerical technique, by solving the governing equations in MATLAB-SIMULINK environment. It is shown that an increase of isolator period would lead to effective earthquake mitigation. A substantial reduction in top floor acceleration and nearly same drifts for all floors are obtained when the period is higher than 4 secs. Therefore, in long period earthquake regions, medium rise buildings can perform better when the isolator period is set to higher values. As a result, the calibration of isolator parameters are shown to be effective, and thus could be used for optimum performance of the concerned structure.

Keywords: LCRB, long period earthquakes, isolator period, numerical analysis

INTRODUCTION

Background

In Japan, during the 2011 Great East Japan Earthquake, buildings were shaken significantly even if they were located far from epicenter. Strong and long lasting motions were observed in regions such as Osaka, Nagoya, Tohama and Tokyo [1]. An interesting example of long period occurrence is a 52 story building located in Osaka 770 km from epicenter, where its top floor displacement was around 1.32 m. The response spectrum of Osaka area has a dominant period of around 6 sec which corresponds to the predominant period of the long period ground motions occurred in deep sedimentary plains of Osaka area [2]. Due to this long period motion, tall buildings suffered mostly from resonance, because of their natural periods which are nearly equal to that of such a ground motion.

Previous Studies Related to Long Period Ground Motions

The behavior of buildings isolated by Lead Core Rubber Bearing (LCRB) during long period ground motions is shown in some researches including [3, 4]. In [5], an isolated 8 storey building is analyzed, and a reduction of floor accelerations is achieved. However, base acceleration is shown to be higher than the input earthquake acceleration. Both numerical and experimental studies are conducted for a 5 storey structure isolated by LCRB [5]. The results are shown to have a good agreement, but a small increase in storey and base floor accelerations are remarked compared to the input acceleration. However, there are some studies where both base and top floor accelerations are almost similar, thus demonstrating rigid body motion characteristics [6, 7]. In the very recent study of Kasimzade [8], it is shown that for the purpose of effective mitigation of long period earthquake for middle rise buildings, the LCRB period should be set to 6 sec. In order to optimize the parameters of LCRB isolator to be used in long period motion basins, more research regarding the performance of this isolator needs to be conducted as the related existing literature is still insufficient. In this study authors aim to optimize the parameters of isolator including its period for the sake of substantial performance of medium rise buildings exposed to long period earthquakes.

METHODOLOGY AND NUMERICAL SIMULATIONS

Defining Governing Equations

A fixed base structure exposed to earthquake load is governed by the equation shown below:

$$[M_S]\{\ddot{U}_S\} + [C_S]\{\dot{U}_S\} + [K_S]\{U_S\} = -[M_S]\{R\}(\ddot{u}_g) \quad (1)$$

A base isolated building by using LCRB is governed by equations shown below:

a) The superstructure part of the building is governed by the equation:

$$[M_S]\{\ddot{U}_S\} + [C_S]\{\dot{U}_S\} + [K_S]\{U_S\} = -[M_S]\{R\}(\ddot{u}_g + \ddot{u}_b) \quad (2)$$

Where, [Ms], [Cs] and [Ks] are the mass, damping and stiffness matrices of the superstructure, respectively; $\{U_S\} = \{U_1, U_2, \ldots U_N\}^{\mathrm{T}}$, $\{\dot{U}_S\}$ and $\{\ddot{U}_S\}$ are the unknown floor displacement, velocity and acceleration vectors, respectively; U_j is the lateral displacement of j^th^ floor relative to the base mass; $\ddot{u}_b$ and $\ddot{u}_g$ are the relative acceleration of base mass and earthquake ground acceleration respectively; and {R} is the vector of influence coefficients.

b) The equation of motion for the base part of the building is expressed as:

$$m_b\ddot{u}_b + F_b - k_1 u_1 - c_1\dot{u}_1 = -m_b\ddot{u}_g \qquad (3)$$

Where m_b and F_b are base mass and restoring force developed in the isolation system, respectively; k_1 is the story stiffness of first floor; and c_1 is first story damping. To find the value of hysteretic restoring force F_b , this study refers to the equation developed by Wen [9] as shown below:

$$F_b = c_b\dot{u}_b + \alpha k_b u_b \ (1-\alpha) f_y Z \qquad (4)$$

In equation (4), f_y refers to yield force, α stands for the ratio of post-yield to pre yield stiffness and finally Z is a component of Wen's non-linear model and can be described via equation (5).

$$\dot{Z} = [A\dot{u}_b - \beta|\dot{u}_b|Z|Z|^{n-1} - \tau\dot{u}_b|Z|^{n}]u_y^{-1} \qquad (5)$$

Here, u_y is yield displacement and can be calculated for particular structure as described in ASCE 41-13.

(β, A and τ) are dimensionless components, these parameters are defined based on laboratory experiments. n is a constant value, and this checks the transition from elastic to plastic behavior of the model.

- *Calculation LCRB Parameters*

Preliminary analytical properties of seismic isolator (k_b, c_b, F_y, u_y) could be calculated based on the following equations [10].

$$k_b = \left(\frac{2*\pi}{T_b}\right)^2 * \left(M_{sup} + m_b\right), \ w_b = \frac{2*\pi}{T_b} \qquad (6)$$

$$\xi_b = 0.15 \ ,$$

$$c_b = 2 * \xi_b * \left(M_{sup} + m_b\right) * w_b \quad ,g = 9.81 \qquad (7)$$

$$Fo = 0.0159, \ W = M * g$$

$$F_y = Fo * W, \ u_y = \frac{F_y}{k_b} \qquad (8)$$

Here,k_b,c_b, F_y and u_y are horizontal stiffness matrix, damping matrix, yield force and yield displacement of seismic isolator respectively. M_{sup} is the total mass of superstructure

Characteristics of Used Earthquakes

In this study, long period earthquakes considered are: Tohoku, Angol and Elmayor earthquakes. The records for these earthquakes are downloaded from the Center of Engineering Strong Ground Motion (CESMD). Ground accelerations of these earthquakes are shown below:

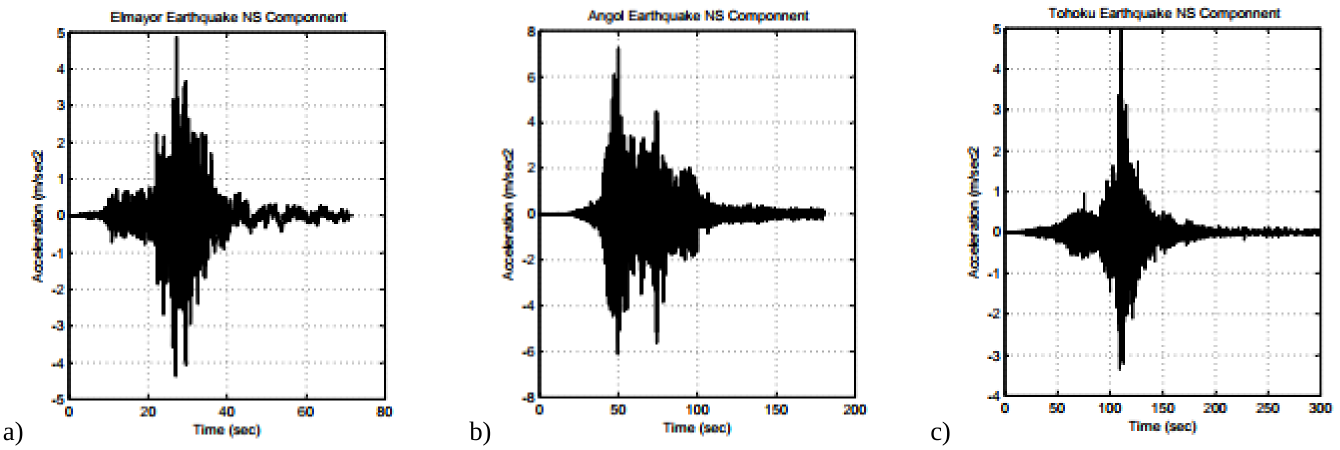


Fig.1. Input earthquake accelerations: a) Elmayor b) Angol) c) Tohoku

By taking Fast Fourier Transforms (FFT) of these components it was possible to find the maximum earthquake period (Te) for every earthquake, and these periods are shown in the table 1. This table clearly shows that these earthquakes had very long periods, and would affect any structure in a number of ways. Table 2 shows description of other long period records, their maximum periods as well as their record stations. It is also shown that these earthquakes had long period motions and would cause unexpected responses.

Table 1. Studied earthquakes frequencies and period values

Earthquake Name	Tohoku	Angol	Elmayor
Frequency(Hz)	0.171	0.259	0.134
Earthquake Period(sec)	5.85	3.85	7.44

Table 2. Description of long period Earthquake records and their maximum period (Te)

Earthquake name	Year	Duration (sec)	City or Basin	Station	Te (sec)
Tonankai	1944	145	Osaka	OSK005	3-5
Tonankai	1944	145	Nagoya	ALC003	3-4
Tonankai	1944	145	Toyama	TYM005	2-3
Tonankai	1944	145	Kofu	YMN005	4
Seoffki peninsula	2004	120	Osaka	OSK005	3
Seoffki peninsula	2004	180	Toyama	TYM005	6
Seoffki peninsula	2004	180	Tokyo	TKY007	7-12
Tohoku G.E.J	2011	299	Shinjuku	TKY007	6
Elcentro	1940	56.52	Imperial valley	1173247N	8

NUMERICAL STUDY

Characteristics of Studied Structures

In this study, storey mass was considered as lumped mass at the center of each floor. Storey stiffness was calculated based on columns dimensions. The building is assumed to have damping characteristics. The building is then isolated by Lead Core Rubber Bearing (LCRB), and the properties of this isolator as well as structural characteristics are shown in Table 3.

Table 3. Description of Isolator parameters

Parameter	Value	Units
Masses (m_1,m_2,m_3,m_4,m_5)	Structural masses are similar for all floors=5897	Kg
Base mass (m_b)	6800	Kg
Stiffness (k_1,k_2,k_3,k_4,k_5)	33732e3, 29093e3, 28621e3, 24954e3, 19059e3	N/m
Damping(c_1,c_2,c_3,c_4,c_5)	Will be calculated based on Rayleigh Formula	N. s /m
β	0.3	NA
A	1	NA
τ	0.7	NA
n	2	NA
α	0.1	NA

NA: Not Applicable

In matrix form, mass and stiffness matrices for studied structure are shown below:

$$M = \begin{bmatrix} m_b & 0 & 0 & 0 & 0 & 0 \\ 0 & m_1 & 0 & 0 & 0 & 0 \\ 0 & 0 & m_2 & 0 & 0 & 0 \\ 0 & 0 & 0 & m_3 & 0 & 0 \\ 0 & 0 & 0 & 0 & m_4 & 0 \\ 0 & 0 & 0 & 0 & 0 & m_5 \end{bmatrix}$$

$$K = \begin{bmatrix} k_b & 0 & 0 & 0 & 0 & 0 \\ 0 & k_1+k_2 & -k_2 & 0 & 0 & 0 \\ 0 & -k_2 & k_2+k_3 & -k_3 & 0 & 0 \\ 0 & 0 & -k_3 & k_3+k_4 & -k_4 & 0 \\ 0 & 0 & 0 & -k_4 & k_4+k_5 & -k_5 \\ 0 & 0 & 0 & 0 & -k_5 & k_5 \end{bmatrix}$$

The construction of damping matrix (C) matrix is based on "Rayleigh Method" and requires two important coefficients which are α_0 and α_1. These are calculated from natural frequencies of the fixed base structure as shown in [11-13]. The general equation for calculating the damping matrix (C) is shown below:

$$[C] = \alpha_o[M] + \alpha_1\,[K] \tag{9}$$

The values of α_0 and α_1 are calculated as shown below:

$$\frac{1}{2}\begin{bmatrix} \frac{1}{w_i} & w_i \\ \frac{1}{w_j} & w_j \end{bmatrix}\begin{Bmatrix} \alpha_0 \\ \alpha_1 \end{Bmatrix} = \begin{Bmatrix} \xi_i \\ \xi_j \end{Bmatrix} \tag{10}$$

In order to be able to solve the above equation, damping ratio is assumed to be the same [16].

Method of Solution

In this study, the governing equations (1 to 5) are solved by using SIMULINK. Responses of interest are plotted and their maximum values are used to analyze the structure effectively.

Solution by Using Simulink

Equations 1 to 3 are first combined to represent the building as a whole and then transformed into a state-space form of first order equations i.e., a continuous-time state-space model of the system. Furthermore, the existing Simulink Block, named "State Space", is used to solve the already transformed equation. Referring to researchers [14-16], the differential equations of a lumped linear network are written in the state form as:

$$\dot{x}\,(t) = Ax(t) + \;Bu(t) \tag{11}$$

$$y(t) = Cx(t) + Du(t)$$

Where,

$$A = \begin{bmatrix} S & I \\ -M^{-1} * K & -M^{-1} * Ci \end{bmatrix}$$

$$B = \begin{bmatrix} SZ & SS \\ -II & M^{-1} * Dis \end{bmatrix}$$

Where, $C = eye(2*N, 2*N)$, i.e. an identity matrix with the same size as A, $D = Zeros(2*N, 2)$, i.e. a zero matrix, N is the number of degrees of freedom in the system; I is an identity matrix of the size N by N , S is a zero matrix of size N by N , II is a matrix with ones and its size is N by 1, SZ is a zero matrix with size N by1, SS is a zero matrix with size N by 1, Dis is a force distribution matrix, which takes dimension based on number of storey being analyzed. M, K and Ci are the mass, stiffness and damping matrices respectively. The other blocks required to build SIMULINK are integrators, multipliers and adders. Furthermore, as shown above, matrices are arranged such that they include nonlinear parts of isolator. After solving the above shown state space equations, displacements and velocities responses are obtained. To calculate accelerations, a derivative block can be used for the already obtained velocities. Blocks used to form SIMULINK diagram are chosen based on references [17]. Model configuration parameters are set based on the recommendations shown in [18] for solving equation of a dynamic system. In the constructed diagram, there are two different input forces: one is seismic load and the other is hysteretic force from lead core component of LCRB. SIMULINK master block model, as well as its inner subsystems are shown below for clarity.

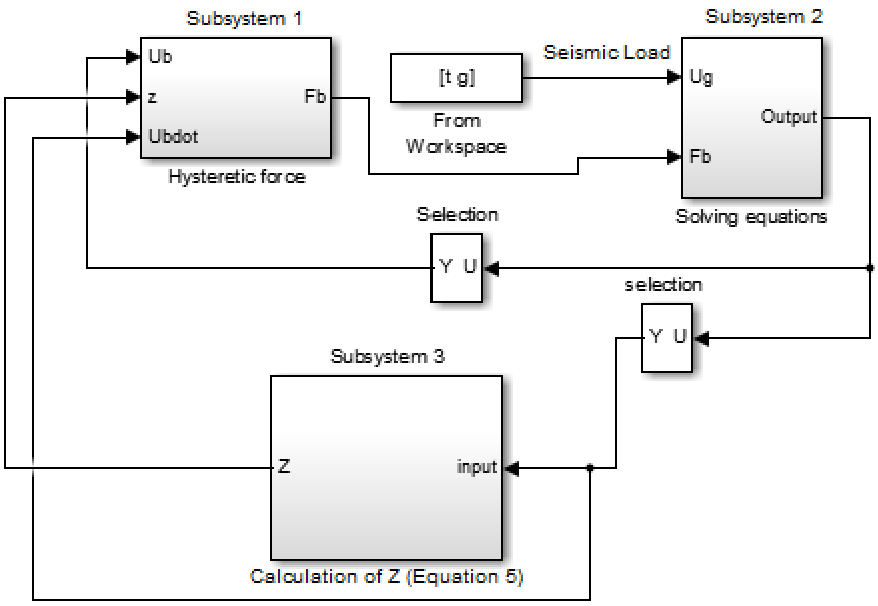


Fig.2. SIMULINK Master Block diagram for modelling isolated structure by LCRB isolator.

The subsystems shown in the above master model diagram are shown below for clarity.

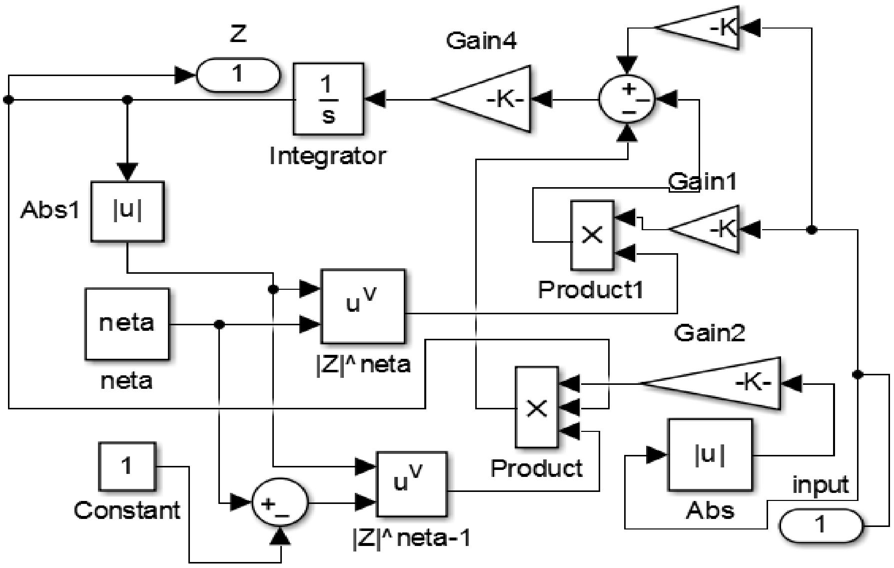


Fig.3. Calculation of Z (Subsystem 3)

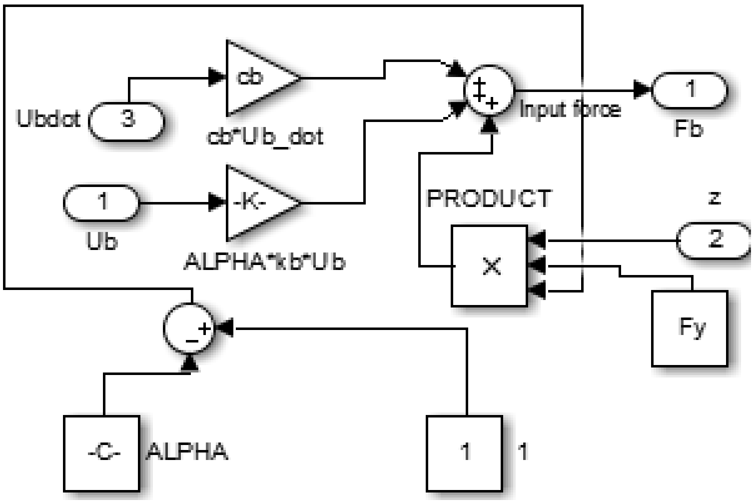


Fig.4. Calculation of Hysteretic force (Subsystem 1)

RESULTS AND DISCUSSION

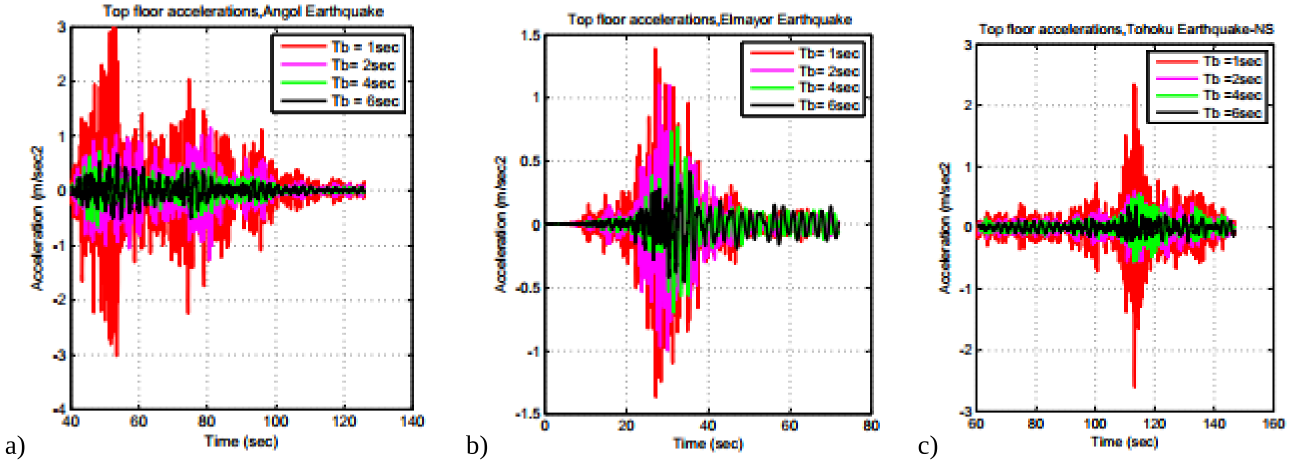


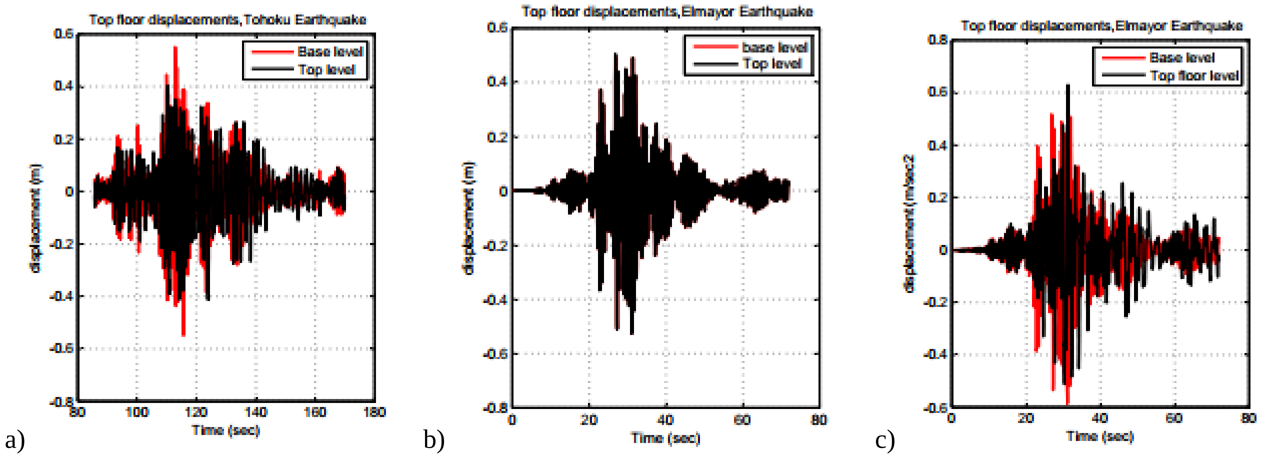
Fig.5. Comparison of top floor acceleration reduction for different isolator period (Tb) during Angol (left), Elmayor (middle) and Tohoku (right) earthquakes.

The accelerations responses for various isolator periods under various types of earthquakes are shown above. It is clear that Tb equal to 6 sec was the best to reduce acceleration, while Tb of 1 sec was the least.

Table 4. Maximum top floor accelerations for different isolator periods during Tohoku, Angol and Elmayor long period earthquakes.

Isolator period-Sec Earthquake Names	1	2	3	4	5	6
Tohoku NS component	2.627	0.906	0.861	0.560	0.449	0.349
Angol NS component	3.044	1.247	0.810	0.715	0.670	0.565
Elmayor NS component	1.390	1.104	0.941	0.766	0.642	0.461

Table 4 shows that, for all the earthquakes used in this study, the highest reduction in top floor accelerations was found for isolator period of 6 sec and the lowest for period of 1 sec. Thus revealing that the performance of isolator would be higher as its period increases. It is also clear that Tb = 4 sec would perform less compared to Tb = 6sec.



a) b) c)

Fig.6. Comparison of top and base floor displacements during Tohoku at Tb = 4sec (a), and Elmayor at Tb = 4sec (b), and Tb = 6sec (c)

Table 5 Comparison of maximum top and base floor displacements for Tb = 4 and 6 secs under various earthquakes.

Earthquake Name	Period(Tb) in sec	Base displacement(m)	Top displacement(m)
Tohoku NS	4	0.558	0.415
	6	0.598	0.613
Angol NS	4	0.522	0.572
	6	0.571	0.581
Elmayor NS	4	0.526	0.517
	6	0.586	0.601

Table 6. Maximum base and storey floor displacements for Tb = 4 and 6 secs under various earthquakes

Earthquake Name	Tb(sec)	Base	1st storey	2nd storey	3rd storey	4th storey	Top storey
Tohoku NS	4	0.558	0.551	0.540	0.547	0.549	0.415
	6	0.598	0.599	0.599	0.602	0.607	0.613
Angol NS	4	0.522	0.524	0.532	0.542	0.552	0.572
	6	0.571	0.572	0.574	0.576	0.579	0.581
Elmayor NS	4	0.526	0.529	0.534	0.531	0.530	0.547
	6	0.586	0.588	0.590	0.592	0.595	0.601

In Figure 6, It is clear that the floor displacements from isolator period of 6 secs are quite similar to the ones from Tb = 4 sec. However, the latter period doesn't successfully keep inter-storey drifts almost similar along the height of building. This is shown mostly at 2nd and top storey levels where displacements alter significantly compared to other floor levels. Therefore, higher period would generally show good performance during long period earthquakes for medium rise buildings. From table 5, it is noticeable that base and top floor displacements would be quite similar, thus causing the whole structure to have significant reduction in drifts when Tb is higher than 4 sec. Table 6 shows displacements for all storeys, and it is also shown that floor displacements increase linearly for higher Tb, contrarily to the displacements for lower Tb values.

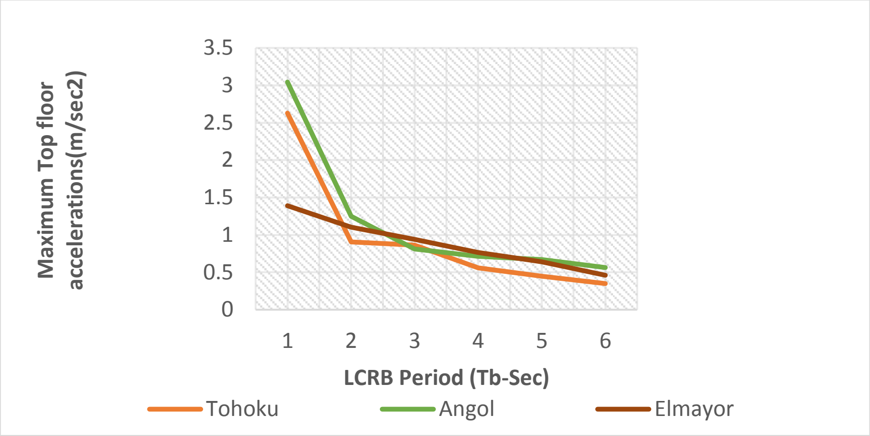


Fig.7. Comparison of top floor accelerations Vs isolator period for a five storey isolated building under different types of earthquakes

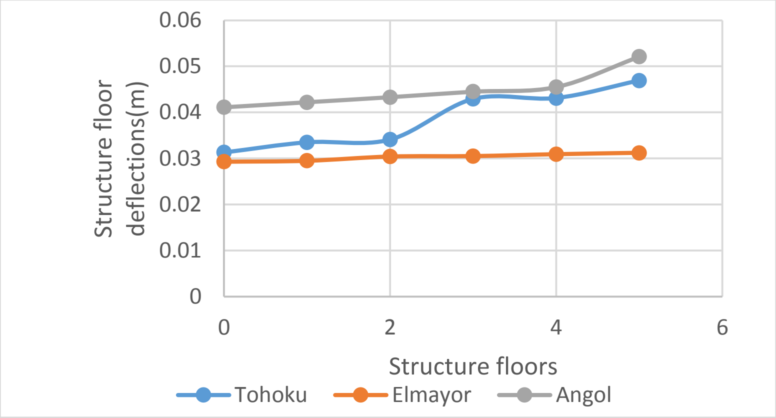


Fig. 8.a. Comparison of maximum floor deflections at Tb= 6secs (b) for a five storey isolated building under different types of earthquakes

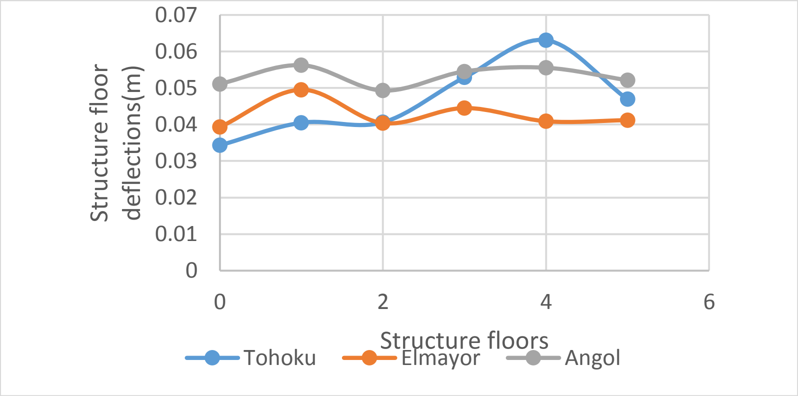


Fig. 8.b. Comparison of maximum floor deflections at Tb= 4secs (b) for a five storey isolated building under different types of earthquakes

As shown in Figure 7, the more the Tb increases the more the maximum top floor acceleration is reduced and the more the earthquake mitigation is obtained. Furthermore, it is shown that the isolator period of 6 sec was the best in reducing accelerations compared to all other Tb values. Figure 9 shows that Tb of 6 secs would keep drifts almost similar while drifts alter significantly for Tb of 4 secs.

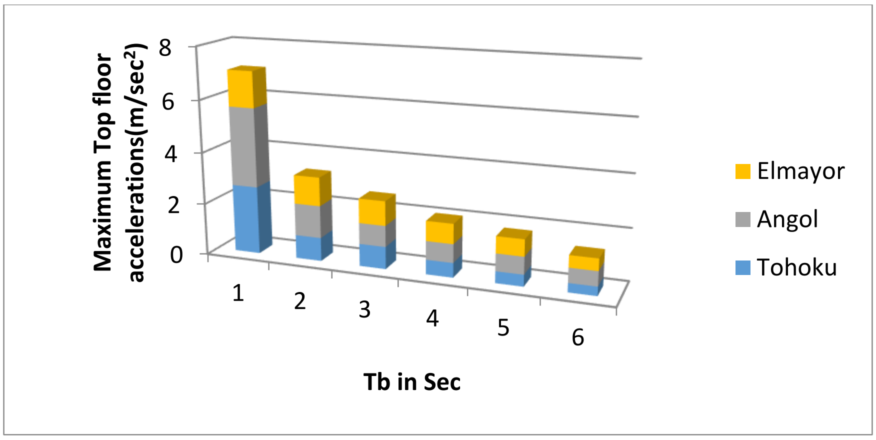


Fig.9. Maximum accelerations for different earthquakes

In Figure 8.a. it is clear that the isolation system for both Elmayor and Angol earthquakes would mitigate the earthquake input force by keeping the deflections almost equal at all floor levels, thus leading to rigid body motion characteristics. However, Tohoku earthquake would cause slight differences in floor deflections but those differences would not cause cracks as their values are smaller compared to the recommended standard values [14]. In Figure 8.b. it is shown that floor deflections would be higher compared to the previous results in Figure 8.a. This indicates that the isolator with Tb = 6sec would perform better than other smaller values, and hence for such long period ground motion, it is necessary to use isolators which are horizontally flexible enough with higher periods as well as higher displacements than the existing isolator design specifications.

CONCLUSION AND RECOMMENDATIONS

In this study the optimum performance of using LCRB as a base isolation system for medium rise building exposed to long period ground motions has been investigated. The main conclusions and recommendations are shown below:

1. The isolation system for medium rise buildings would result in a good performance if the isolator period is risen for higher than 4sec.
2. The optimum of new-to-design isolators should be calibrated based on the parameters shown in this study if they are to be used in regions with long period motions.
3. Floor displacements as well as floor deflections are well controlled when Tb higher than 4 sec is used during long period earthquakes.
4. Reduction in top floor accelerations and similar drifts are obtained for isolator of period higher than 4 secs, while the periods less or equal to this value may reduce the acceleration but fail to keep the building move as a rigid body, which is a key to crack prevention.
5. The study would recommend to use the isolator design period higher than existing value when it comes to mitigating the long period ground motions.
6. More studies on isolation system under long period earthquakes need to be conducted, especially by comparing experimental and analytical studies in order to strengthen and renew the existing code standards, and also to set LCRB optimized values during long period ground motions.

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