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# OPTIMUM MODAL CHARACTERISTICS FOR MULTI-STORY BUILDINGS ISOLATED WITH LRBS

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## ABSTRACT

Improving the performance of available base-isolation technologies in conjunction with optimum using of dynamic properties of superstructure such as stiffness, damping and mass has gained lot of interests in the earthquake engineering field. In this study, the effect of superstructure characteristics on performance of multi-story buildings isolated with lead-plug laminated rubber bearings has been investigated. The superstructure characteristics considered at current research are superstructure mass, superstructure stiffness and superstructure damping, which were varied in the range that is compatible with engineering practice. Comparing the study results it has been observed that, there is optimum amount for each of the dynamic properties of the superstructure which will make design criteria achievable in seismic base-isolation of multi-story buildings. To this purpose, five reinforced concrete moment resisting frame buildings with two, five, nine, fourteen and twenty stories were considered. They were designed according to UBC97, in fixed-base form and base-isolated form. Five different amount for superstructure base-mass were assigned and 25 related models were created. Variations in superstructure stiffness and superstructure damping were considered in the same manner. All of 85 model buildings were subjected to five ground motion records which have been scaled to have PGA = 0.4g. Nonlinear time-history analyses of created models were conducted by using ETABS 8.5.0. Fundamental periods, modal participation factors and base-shears were studied for all of the model buildings. Comparing analysis results in term of base shear variations for different parameters considered, it was concluded that, superstructure characteristics have considerable effect on performance of isolated systems and optimal performance of base isolated multi-story buildings is achievable by modifying superstructure characteristics. It was shown that, performance of low-rise base isolated buildings is not so sensitive to the variation in superstructure characteristics, while adding base-mass and increasing the damping of superstructure in middle-rise buildings will improve the isolation performance. Also, increasing stiffness and damping of superstructure can result in effective isolation and improved seismic behavior in high-rise buildings.

Key words: Structural Control, Passive Control, Base Isolation, Seismic Isolation, Modal Characteristics, Superstructure Characteristics, Lead-plug Laminated Rubber Bearings.

## INTRODUCTION

Environmental loads, such as earthquakes, can seriously damage, or even destroy structures. The strengthening of structure to withstand extreme environmental dynamic loads can be uneconomical or impractical; moreover, constructing a conventional building with the strength to withstand large seismic motion may lead to a situation where the structure is undamaged, but the structure's contents are damaged or destroyed, and the structure's occupants injured. So, most codes allow us to use ductility (Nagarajaiah et al., 1998 - Kelly T.E., 2001).

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These customary methods that increase the capacity of structure will be neither rational nor acceptable. In spite of these methods, there are some other methods that use different strategies applying structural control technologies. Of these acceptable methods, base-isolation can now be considered a more mature technology with wider applications as compared with the other methods. Base-isolation reduces demand instead of increasing the capacity, indeed it works in base level of the structure that is the interface of the structure and the underlying soil. So, this method will be more rational rather than other methods of structural control (Kelly T.E., 2001 - Skinner et al., 1993 - Soong TT. et al., 2002 - Housner G.W. et al., 1997).

Although literature review refers base-isolation idea to the approximately two hundred years ago, but documents show that the first proposal was from J.A. Calantariants in 1909. In August 1909 he wrote a letter to the director of the Seismological Service of Chile in Santiago calling his attention to a method of building construction that he had developed whereby "substantial buildings can be put up in earthquake countries on this principle with perfect safety since the degree of severity of an earthquake loses it significance through the existence of the lubricated free joint". He has submitted a patent application for his method which proposed that the building be built on his " free joint " and a layer of fine sand, mica or talc that would allow the building slid in an earthquake, thereby reducing the force transmitted to the building itself. It would be surprisingly to say that he was a medical doctor. There are some references to J. Milne that used a system of base isolation with cast-iron balls in 1876, too (Naeim and Kelly, 1999). Anyway, the concept of seismic base isolation has become a practical reality within the last twenty years (Chopra, 1995).

Base-isolation generally falls into the passive category of structural control, while it can be active or passive. Nowadays there are some applications of base-isolation in the form of hybrid control or in the form of semi-active control and most of the researches are concentrated on the use of smart materials in base-isolation. Anyway, we know that the goal of seismic base isolation has been the completely isolating structures from earthquakes, but it can not be gained, yet. After initial proposals and practical uses of sliding systems and elastomeric systems, many other systems were proposed but there is no real base-isolation system. So, there are two major challenges in this field of structural engineering and researchers try to create new real base-isolation systems or to improve the performance of present base-isolation technologies. Obviously, improving the performance of present base-isolation technologies can be more useful for developing countries.

As an investigation on isolation performance, Fan and Ahmadi (2003) have studied the sensitivity of base-isolation systems to the variation of earthquake properties and also superstructure characteristics. It has been shown that sliding systems have less sensitivity to the input motion properties and superstructure characteristics than other isolation systems.

Hong and Kim (2004) in their paper have investigated the effects of damping and stiffness of both superstructures and isolators. They have showed that by stiffening superstructure we can obtain more reduction in displacements rather than accelerations. Moreover they showed that the effect of damping in fixed-base structures is more than base-isolated structures.

Matsagar and Jangid (2004) have concluded that in designing base-isolated structures one has to consider the effects of superstructure characteristics. They have observed that assuming rigid superstructure is not conservative and this assumption will probably cause incorrect results. For example by using rigid superstructure acceleration will be lower than actual one in the top story. For isolator displacements, however, we can use rigid structure assumption.

Thakkar and Jain (2004) through their investigation by analyzing ten, fourteen and twenty story buildings have concluded that by stiffening superstructure, in high-rise buildings, one can improve the performance of base-isolation.

In this study, we are concentrated on improving the performance of present base-isolation systems. Base-isolation performance depends on various parameters: earthquake characteristics, soil dynamic properties, mechanical properties of isolation systems and superstructure characteristics. Superstructure characteristics are considered, in this research. Mass, stiffness and damping are the basic dynamic parameters of structures that define modes and mode shapes. Varying these characteristics will definitely improve the base-isolation performance. By studying these effects we have determined optimum characteristics and are able to have improved base-isolation performance.

At the first, we have to choose a proper base-isolation system and also a proper structural type. The most crucial part of the process is also choosing proper analysis methods.

Existent practical base isolation systems are: Laminated rubber bearings(LRB), High damping rubber(HDR), Lead-plug laminated rubber bearings(L-LRB), Fiber-reinforced rubber bearings(FRB), Friction pendulum systems(FPS), Resilient friction base-isolation systems(R-F B) and also some other systems which are not mentioned because of their less practical usage.

From these systems, L-LRB has been used most and is well-known. So, we have selected this system for our study. Fig. 1 presents the simplest type of this system:

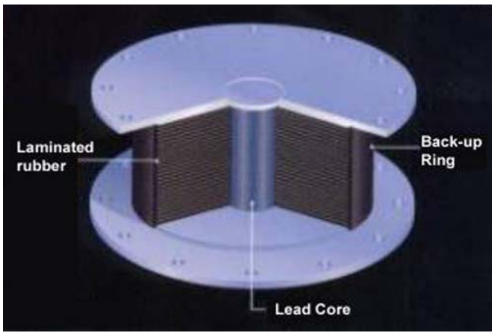

Figure 1: L-LRB

Superstructure can be a building, bridge, power plant or in the other forms of structures. Multi-story buildings are more relevant to current study because of their extensive use in our modern time and urbanized world. So, we are concentrated on building structures.

Nonlinear time-history analysis by Ritz vectors is used because of the nonlinearity of isolation system exclusively in lead plug. We have conducted time-history analysis in order to get more exact results as outlined in UBC97. For more accurate results we have used Ritz vectors in nonlinear time history analysis.

In order to investigate the effects of superstructure characteristics on isolation performance, five reinforced concrete moment resisting framed buildings with 2, 5, 9, 14 and 20 stories have been considered. Their mass, stiffness and damping have been varied, in model buildings isolated with lead-plug laminated rubber bearing. By conducting nonlinear time history analyses of the model buildings the effects of the above mentioned parameters have been examined. The results have been compared for each category and that of the fixed base and isolated buildings.

## BASIC CONCEPTS

Ideal base-isolation that completely isolates structural building from its moving base has not been gained yet, and at the present time we are only trying to reduce the effects of earthquakes on structures by using base-isolation (Kelly T.E., 2001). This effort can be improved by using proper characteristics of superstructure, selecting proper isolation system, considering sub-soil properties and also the characteristics of earthquakes (Jain and Thakkar, 2004 - Baratta and Corbi, 2004).

We know that eigenvalues and eigenvectors of characteristic equation depend on mass, stiffness and damping of structure. So, as it is obvious from Eqs.1 and 2, mass and stiffness of structures can be called the basic modal characteristics. Note that, damping depends on mass and stiffness.

$$\mathbf{m}\ddot{\mathbf{u}} + \mathbf{k}\mathbf{u} = \mathbf{0} \tag{1}$$

$$\det[\mathbf{k} - \omega_n^2 \mathbf{m}] = 0 \tag{2}$$

It seems that, heavy base slab would be helpful for isolation performance through reducing the transferred movement. This is the case for a pyramid located on a book. It stays stationary when someone pulls the book under it, but a tall rectangular cube might fall down easily (Fig. 2).

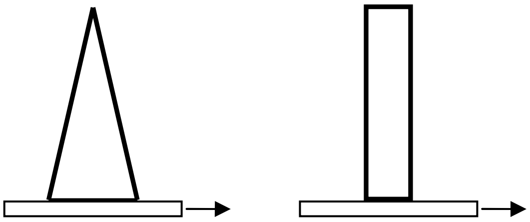

Figure2: The effect of superstructure characteristics

Stiffened superstructure will result in better isolation performance because of its effects on structural deformations which in turn have inevitable influence on isolation performance. And also increasing the damping of superstructure would be useful to mitigate earthquakes. So, the superstructure characteristics will be varied by assigning additional base-mass, increasing the stiffness and increasing the damping.

## MODEL STRUCTURES

The buildings considered for this analytical study are five reinforced concrete moment resisting framed buildings with 2, 5, 9, 14 and 20 stories. They are designed according to UBC97, in both fixed-base form and base-isolated form. The isolation systems are lead-plug laminated rubber bearings. The properties of these model buildings are given in Table 1.

Table 1: Properties of model structures

| ***Buildings*** | ***Fixed-base form*** | | ***Base-isolated form*** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ***First story columns*** *(mm×mm)* | ***First story beams*** *(mm×mm)* | ***Isolator*** | | | | | | ***Superstructure*** | |
| | | | *P.D.* *(mm)* | $K_{eff}$ *(N/m)* | $K_1$ *(N/m)* | *Fy* *(N/m)* | *R* | $D_{eff}$ | ***First story columns*** *(mm×mm)* | ***First story beams*** *(mm×mm)* |
| ***2 story*** | 450×450 | 450×350 | 500 | 1255000 | 6275000 | 3137000 | 0.25 | 0.08 | 350×350 | 325×225 |
| ***5 story*** | 550×550 | 500×400 | 750 | 1610000 | 8050000 | 4020000 | 0.2 | 0.1 | 450×450 | 400×300 |
| ***9 story*** | 700×700 | 600×500 | 950 | 2115000 | 10570000 | 5287000 | 0.15 | 0.15 | 550×550 | 500×400 |
| ***14 story*** | 800×800 | 650×500 | 1250 | 2513000 | 12565000 | 6300000 | 0.13 | 0.2 | 750×750 | 600×450 |
| ***20 story*** | 1000×1000 | 700×650 | 1500 | 3821000 | 19105000 | 9500000 | 0.1 | 0.25 | 950×950 | 700×650 |

*P.D.: Plan Diameter*, $K_{eff}$ *: Effective Stiffness*, $K_1$ *: Initial Stiffness of Bilinear Model*, $F_y$ *: Yielding Force*

$R$ *: The Ratio of* $K_2$ *to* $K_1$ *in Bilinear Model*, $D_{eff}$ *: Effective Damping*

The variations of superstructure characteristics; base-mass, stiffness and damping, have been done for five different amounts. For superstructure base-mass they are +10kN, +20kN, +30kN, +40kN and +50kN. The superstructures stiffness considered are obtained by changing modulus of elasticity E to 1.5E, 2E, 2.5E, 3E and 3.5E. And finally, damping amounts used in analyses are $\zeta = 0.10$, $\zeta = 0.15$, $\zeta = 0.20$, $\zeta = 0.25$ and $\zeta = 0.30$.

So, there are 85 model buildings; five models for fixed-base buildings, five models for base-isolated buildings and seventy-five models for variation of the superstructure characteristics in each base-isolated building.

## EARTHQUAKE EXCITATIONS

Five ground motion records are used. They are scaled to have peak ground acceleration equal 0.4g (PGA = 0.4g). The detailed information for all records is given in Table 2. Note that in this table, *D* is the distance from source.

Table 2: Earthquake excitations

| *Name* | *Date* | *Station* | *Component* | *PGA(g)* | *M* | *D(km)* |
|---|---|---|---|---|---|---|
| ***Northridge*** | 1994/01/17 | LA-UCLA | UCLA-360 | 0.474 | 6.7 | 14.9 |
| ***Livermore*** | 1980/01/27 | Morgan Terr Park | BLMO-355 | 0.252 | 5.4 | 8 |
| ***Parkfield*** | 1996/06/28 | Cholame#8 | C08-320 | 0.273 | 6.1 | 9.2 |
| ***Imperial Valley*** | 1979/10/15 | Agrarias | H-AGR 273 | 0.221 | 6.5 | 12.9 |
| ***Tabas*** | 1978/09/16 | Tabas | TAB-TR | 0.852 | 7.4 | unknown |

## ANALYSIS RESULTS AND DISCUSSION

In order to investigate the effects of superstructure characteristics on isolation performance, nonlinear time-history analyses by Ritz vectors are conducted using ETABS 8.5.0. Fundamental periods, modal participation factors and base shear forces are studied. Comparing base-isolated building with fixed base building, the efficiency of isolation is examined. The effects of variations of superstructure characteristics are investigated comparing fundamental periods, modal participation factors and base shear forces with those in base-isolated buildings of no variation in superstructure characteristics. These results are given here, for each of the 2, 5, 9, 14 and 20 story buildings. A final discussion at the end of the section defines that the effects of superstructure characteristics on isolation performance are different in buildings of different heights. As the result of this trend, buildings are categorized into low-rise buildings, middle-rise buildings and high-rise buildings.

### Two-story Building

Following subsections describe that in two-story building base-isolation has good performance, because of reduction in the participation of structural modes and the base shear compared to those in fixed-base building. Increasing base-mass reduces the participation of superstructure but in contrast base shear force increases, so it can not be useful to improve the base-isolation performance. There is same situation for the variation of superstructure stiffness, too. Increasing the damping is helpful but it can not be applied in general, because of its cost comparing with the costs of building itself.

### *Comparison of Results for Fixed-base and Base-isolated Building*

First mode period becomes 3.5 times longer in base-isolated building than it is in fixed-base building. So, it seems that base-isolation will reduce the effect of earthquakes on superstructure. It would be obvious reminding the general nature of earthquake spectra, in which there are low accelerations for long periods.

Comparing modal participation factors shows that there is a decrease in the participation of structural modes. For the first structural mode in base-isolated building, it is 0.2 times of its amount in the fixed-base building. The effect of earthquakes on building will decrease.

Base shear decreases in base-isolated building comparing with fixed-base building. In the case of Northridge earthquake, it decreases from 3432211N in fixed-base case to 2102049N in base-isolated case. There is almost the same reduction in Livermore earthquake from 4195697N to 2400134N. These reductions are 52%, 55% and 56% for Parkfield, Imperial Valley and Tabas earthquakes, respectively.

### *Effects of Increasing Base-mass*

By increasing base-mass the isolation period increases, as it is expected. Modal participation factors increase in isolation modes and decrease in structural modes. Table 3 shows the variations of base shear.

In this table, $\Delta V_i^m$ is calculated according to Eq. 3, where *i* represent the number of cases for which amount of additional base-mass are +10kN, +20kN, +30kN, +40kN and +50kN, respectively .

$$\Delta V_i^m = \frac{V_i^m - V_{base-isolated}}{V_{base-isolated}} \times 100 \quad , \quad i = 1,2,...,5 \tag{3}$$

Table 3: Effect of base-mass increase on base shear for two-story building

| *Excitation* | $\Delta V_1^m$ | $\Delta V_2^m$ | $\Delta V_3^m$ | $\Delta V_4^m$ | $\Delta V_5^m$ |
|---|---|---|---|---|---|
| ***Northridge*** | +12 | +2 | +14 | +44 | +83 |
| ***Livermore*** | -1 | +27 | +49 | +54 | +63 |
| ***Parkfield*** | +11 | +20 | +22 | +44 | +28 |
| ***Imperial Valley*** | +12 | +62 | +73 | +102 | +121 |
| ***Tabas*** | +4 | +22 | +32 | +37 | +60 |

Although the isolation period increases and structural modes participate lesser, base shear cannot be reduced. So, adding base-mass will not improve the performance of base-isolation in two-story building.

### *Effects of Stiffened Superstructure*

The stiffening may result in reduced fixed-base periods. But such building if base isolated may develop smaller seismic response, and as a result of it participation of structural modes decrease. But base shears can not be reduced here, in two-story building. And hence, stiffened superstructure does not improve the isolation performance. Base shear variations are given in Table 4, in which $\Delta V_i^k$ is calculated as Eq. 4.

$$\Delta V_i^k = \frac{V_i^k - V_{base-isolated}}{V_{base-isolated}} \times 100 \quad , \quad i = 1,2,...,5 \tag{4}$$

In this equation, *i* represent the number of cases for variation of superstructure stiffness by 1.5E, 2E, 2.5E, 3E and 3.5E, respectively.

Table 4: Base shear variations in stiffened superstructure for two-story building

| *Excitation* | $\Delta V_1^k$ | $\Delta V_2^k$ | $\Delta V_3^k$ | $\Delta V_4^k$ | $\Delta V_5^k$ |
|---|---|---|---|---|---|
| ***Northridge*** | +2 | +4 | +4 | +10 | +21 |
| ***Livermore*** | -11 | +21 | +33 | +50 | +69 |
| ***Parkfield*** | +53 | +56 | +81 | +78 | +64 |
| ***Imperial Valley*** | +33 | +108 | +121 | +129 | +127 |
| ***Tabas*** | +29 | +75 | +87 | +156 | +196 |

### *Effects of Increased Damping*

Increasing the damping of superstructure, base shears decrease comparing with those in base-isolated building of having $\zeta = 0.02$ for superstructure. Calculating the variations of base shears by using Eq. 5, results are obtained and are given in Table 5.

$$\Delta V_i^D = \frac{V_i^D - V_{base-isolated}}{V_{base-isolated}} \times 100 \quad , \qquad i = 1,2,...,5 \tag{5}$$

Note that, in this equation *i* represent number of cases in which damping of superstructure are ζ= 0.10, ζ= 0.15, ζ= 0.20, ζ= 0.25 and ζ= 0.30 respectively.

Table 5: Base shear variations due to increased damping for two-story building

| *Excitation* | $\Delta V_1^m$ | $\Delta V_2^m$ | $\Delta V_3^m$ | $\Delta V_4^m$ | $\Delta V_5^m$ |
|---|---|---|---|---|---|
| ***Northridge*** | -7 | -11 | -14 | -18 | -21 |
| ***Livermore*** | -21 | -26 | -30 | -34 | -37 |
| ***Parkfield*** | -20 | -28 | -34 | -39 | -40 |
| ***Imperial Valley*** | -7 | -10 | -12 | -14 | -16 |
| ***Tabas*** | -13 | -15 | -17 | -15 | -21 |

## Five-story Building

In five-story building, assigning additional base-mass has good effect on reducing input energy. Although stiffened superstructure reduces the participation of superstructure but it can not cause considerable reduction in base shears. Increased damping reduces the base shear with various rates, which depend on the amount of damping. The details of these results are given in the following subsections.

### *Comparison of Results for Fixed-base and Base-isolated Building*

First mode period in base-isolated building is 2.3 times longer than that of fixed-base building. Modal participation factor of the fundamental structural mode of base-isolated building is 0.4 times lesser than that of fixed-base building. Base shear decreases by 11% in Northridge earthquake, 35% in Livermore earthquake and 61% in Parkfield earthquake.

### *Effects of Increasing Base-mass*

By increasing base-mass, isolation period will increase. Due to base-mass increase isolation modes participate more and structural modes participate lesser. Base shears variations are given in Table 6. It is concluded that increasing base-mass can be helpful for improving the performance of base-isolation.

Table 6: Base shear variations due to base-mass increase for five-story building

| *Excitation* | $\Delta V_1^m$ | $\Delta V_2^m$ | $\Delta V_3^m$ | $\Delta V_4^m$ | $\Delta V_5^m$ |
|---|---|---|---|---|---|
| ***Northridge*** | +0.5 | -11 | -21 | -18 | -22 |
| ***Livermore*** | +1 | +15 | +9 | -10 | -31 |
| ***Parkfield*** | +32 | +67 | +77 | +46 | +30 |
| ***Imperial Valley*** | -4 | +4 | -2 | -12 | -10 |
| ***Tabas*** | +5 | -9 | -2 | -24 | -32 |

### *Effects of Stiffened Superstructure*

Modal participation factors of structural modes become lesser. But, as given in Table 7, stiffening of superstructure can not be effective in base shear reduction. And hence, stiffening superstructure can not improve the isolation performance.

Table 7: Base shear variations due to stiffened superstructure for five-story building

| ***Excitation*** | $\Delta V_1^k$ | $\Delta V_2^k$ | $\Delta V_3^k$ | $\Delta V_4^k$ | $\Delta V_5^k$ |
|---|---|---|---|---|---|
| ***Northridge*** | -34 | -2 | -3 | -5 | +4 |
| ***Livermore*** | +8 | -6 | +21 | +37 | +61 |
| ***Parkfield*** | +85 | +65 | +61 | +85 | +90 |
| ***Imperial Valley*** | +20 | +32 | +43 | +46 | +45 |
| ***Tabas*** | -33 | -33 | -40 | -35 | -35 |

### *Effects of Increased Damping*

Base shear variations due to increasing damping are given in Table 8. It is evident from the table that increasing the damping of superstructure can be effective in improving the isolation performance.

Table 8: Base shear variations due to increase in damping for five-story building

| ***Excitation*** | $\Delta V_1^m$ | $\Delta V_2^m$ | $\Delta V_3^m$ | $\Delta V_4^m$ | $\Delta V_5^m$ |
|---|---|---|---|---|---|
| ***Northridge*** | -34 | -39 | -42 | -44 | -45 |
| ***Livermore*** | -38 | -42 | -44 | -46 | -48 |
| ***Parkfield*** | -6 | -4 | -4 | -6 | -8 |
| ***Imperial Valley*** | -15 | -13 | -12 | -12 | -13 |
| ***Tabas*** | -41 | -50 | -54 | -57 | -59 |

## Nine-story Building

Nine-story building has the same situation as five-story building. So, for brevity details are not given here.

It must be pointed out that simple base-isolation reduces base shear about 40% in average. Assigning additional base-mass can reduce base shear same as the five-story building. Stiffening superstructure can not do anything to improve the isolation performance, again. Increasing the damping of superstructure, base shear decreases additionally by 50% in average and it can improve the performance of base-isolation.

## Fourteen-story Building

Results show a different situation in the case of fourteen-story building. Simple base isolation in fourteen-story building can not cause a considerable reduction on input energy. Additional base-mass causes some more reduction in base shear, but there is no decrease in participation of structural modes. Stiffening superstructure can result in a reasonable isolation. Increasing damping is helpful, too. The detailed information regarding fourteen-story building is given in the following sections.

### *Comparison of Results for Fixed-base and Base-isolated Building*

Although in base-isolated form first mode period becomes 1.5 times longer than it in fixed-base form, but it can not cause an acceptable reduction in input energy. This would be expectable reminding the general form of earthquake spectra, with less sensitivity of acceleration in long periods.

### *Effects of Increasing Base-mass*

In spite of five-story and nine-story buildings assigning additional base-mass can not result in effective reduction on base shear, even though it will increase the isolation period and also it will cause more participation of isolation modes. The variations of base shear are given in Table 9.

Table 9: Base shear variations due to base-mass increase for fourteen-story building

| *Excitation* | $\Delta V_1^m$ | $\Delta V_2^m$ | $\Delta V_3^m$ | $\Delta V_4^m$ | $\Delta V_5^m$ |
|---|---|---|---|---|---|
| ***Northridge*** | -0.9 | +2 | -6 | -9 | -0.2 |
| ***Livermore*** | -1 | -7 | -15 | -13 | -11 |
| ***Parkfield*** | +16 | +28 | +16 | -2 | -5 |
| ***Imperial Valley*** | -2 | +5 | +10 | +10 | +9 |
| ***Tabas*** | +2 | +2 | +2 | +3 | +1 |

### *Effects of Stiffened Superstructure*

Stiffening superstructure in high-rise buildings improves the isolation performance. This result from current study is in line with the conclusions of the paper written by Dr S K Jain and Dr S K Thakkar (2004). Although the periods decrease but the structural modes participate lesser and isolation modes participate more. It can cause additional reduction in base shear. For example in Tabas earthquake it can reduce the base shear by 10% in average. The reduction in base shear is about 30% for Livermore earthquake.

### *Effects of Increased Damping*

Damping ratio of 10% instead of 0.02 causes an additional reduction of 35% in average. Increasing it into 0.20 reduces base shear 5% more and finally a damping ratio of 0.30 will result in 42% reduction comparing with simple base-isolation. So it can be said that by increasing the damping of superstructure, the performance of base-isolation will be improved.

## Twenty-story Building

The situation in twenty-story building is the same as fourteen-story building. So, it is not discussed in details. In this case again simple base-isolation cannot be acceptable. Assigning additional base-mass cannot do anything to improve the isolation performance. Stiffened superstructure can cause a reasonable isolation. Increasing the damping of superstructure results in more reduction in base shears and improves the isolation performance.

## Final Discussion

There was an interesting trend in the effects of superstructure characteristics on isolation performance. In the case of two-story building there is no need to the variations in superstructure characteristics and these variations will not be useful. In five and nine-story buildings, assigning additional base-mass and increasing the damping of superstructure will improve the performance of base-isolation. In the case of fourteen and twenty-story buildings, it could be said that, stiffening superstructure and increasing its damping will result in a reasonable isolation.

In order to clarify the overall behavior of different buildings considered in this study, buildings can be classified into three categories according to their height. low-rise buildings which comprise buildings shorter than common three-story buildings (15m), middle-rise buildings which are between low-rise and high-rise buildings (15m<are<33m) and finally high-rise buildings with the height taller than 33 meter or those by 12 or more stories. The effect of different parameters on response of structures could vary dramatically according to their height or category they belong to.

## CONCLUSIONS

The effect of superstructure characteristics on base-isolation performance is investigated. A comparison of the fundamental periods, modal participation factors and base shears for 85 created model buildings are carried out. Based on the results of the current research work, following conclusions are drawn.

1. Superstructure characteristics have a considerable effect on isolation performance.
2. By using proper characteristics of superstructure, base-isolation performance can be improved.
3. The characteristics of superstructure have different effects on isolation performance in low-rise buildings, middle-rise buildings and high-rise buildings.
4. In low-rise buildings, simple base-isolation has good performance and there is no need to modify the superstructure characteristics. Indeed, these modifications can not have positive effect on isolation performance.
5. In middle-rise buildings we can reach better isolation by assigning additional base-mass and increasing the damping of superstructure.
6. In high-rise buildings, stiffening superstructure and increasing the damping will cause an effective base-isolation.

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