# EARTHQUAKE RESPONSE ANALYSIS OF MID-STORY BUILDINGS ISOLATED WITH VARIOUS SEISMIC ISOLATION TECHNIQUES

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**ABSTRACT :**

The basic idea of seismic isolation is based on reduction of the earthquake induced inertia loads by shifting the fundamental period of the structure out of dangerous resonance range, and concentration of the deformation and energy dissipation demands at the isolation and energy dissipation systems, which are design for this purpose. In this paper, after a brief introduction, the energy approach to the earthquake resistant structural design is described. As a numerical example, a six story structure analyzed with five different seismic protection alternatives as fixed base, rubber bearing, friction pendulum bearing, additional isolated story and viscous damper. Three dimensional nonlinear time history analysis is performed on r/c building model for fixed base case with respect to the seismic isolation and earthquake protection alternatives. In determining the specifications of isolators and dissipaters, such device features are taken into consideration, which would transfer minimum effects onto the structure as tested by numerous experiments on the basis of the criteria, including base and story shear forces, story accelerations, and relative story drifts while the isolators would undergo reasonable displacements. Nevertheless, such analysis could not provide full optimization; the main objective here is to make a comparison between the seismic isolation and fixed based building, rather than comparing the seismic isolation alternatives within themselves. In the analysis, total base shear forces, story shear forces, maximum absolute accelerations and relative story drifts are compared and results are discussed.

**KEYWORDS:** Seismic Isolation, Response Analysis, Energy Dissipation, Mid-Story Building

## 1. INTRODUCTION

Engineers and architects have been carrying out studies for over one hundred years to find applicable methods to reduce the response given to the ground motions by the structures. Seismic isolation and energy dissipating systems are some of the design strategies applied to increase the earthquake resistance of the structures. In simple words, seismic isolation is a process to decrease the response shown to the impacts such as earthquake by separating the superstructure from the ground. In this way, the period and the damping ratio of the structure isolated from the ground are increased. This, in turn, reduces the earthquake forces on the structure. The increase in damping ration is a natural characteristic for most isolators, and if desired, additional energy dissipating devices may also be installed on to the structure. Storey displacements in the structure together with the accelerations shall be reduced significantly. While this reduction in the accelerations protects the non-structural elements from the acceleration originated damages, the reduction in the storey displacements shall allow both the structural and non-structural elements survive the earthquake without any damage or with little damage. On the other hand, the energy dissipating systems increase the damping ratio, and sometimes the rigidity of the structure. These systems dissipate part of the energy created on the structure by the earthquake effect, and thus increase the seismic performance of the structure and of its contents.

Specific seismic systems such as isolators or energy dissipaters should be evaluated during the design stage of the structure, and if deemed necessary, must be selected in conformity with the targets stipulated for the structure. The stipulated target is the degree of the performance expected from the structure subjected to design earthquake. As the earthquake demand and the expected performance increase, the application of the seismic systems becomes more attractive and feasible.

## 2. ENERGY APPROACH IN SEISMIC DESIGN

The first two things come to mind of the engineers, when earthquake resistant structural design is mentioned, are forces and displacements. However, as the earthquake in fact is an energy originated event, the energy concept is more fundamental phenomenon to think about. Seismic energy also lays in the root of the forces and displacements created by the earthquake effect on the structure. Forces and displacements arise as consequences of this energy.

According to the energy conservation principle, the energy of the earthquake (E) must be equal to the sum of the energy stored within the structure ($E_s$) and the dissipated energy ($E_d$).

$$E = E_s + E_d \tag{2.1}$$

Here; E is the total earthquake energy on the structure. In other words, it is the total work done by the reversible shear force created on the foundation of the structure. $E_s$ is the amount of energy stored in the structure itself within the elastic range. The structure actualizes this storage by converting the earthquake energy into kinetic energy ($E_k$) and elastic strain energy ($E_e$) during its swinging.

$$E_s = E_k + E_e \tag{2.2}$$

$E_d$ is the amount of energy dissipated by the structure, and it has two components, called viscous damping ($E_v$) and hysteretic damping ($E_h$).

$$E_d = E_v + E_h \tag{2.3}$$

While, the viscous damping of the structures, in fact, is a reduction to express many complex mechanisms such as heat created by the intermolecular friction, contribution of the non-structural elements, viscosity of air, etc. Whereas, the hysteretic damping is the expression used for the damping achieved by plastic hinges, cracking, crushing, yield of the reinforcement, in short, by “damage”.

### *2.1. Conventional Approach – Resistance*

If the structures are designed in a manner not to suffer any damage by assuming that the elements remain within the elastic limits during the earthquake, this requires just resorting to $E_k$ and $E_e$ terms. In other words, the path to resist the earthquake in the traditional approach passes through increasing $E_s$. As the energy shall be met by the deformations intensified in certain joint regions of the structure, the strength is increased especially in these regions. However, it must not be forgotten that all the structures has a viscous type damping capacity even if it stays within the elastic limits. For this reason, $E_v$ must also be taken into account. In this case, the energy equation shall be;

$$E = E_e + E_k + E_v \tag{2.4}$$

However, the above approach often exhibits illusion, and the seismic protection can only be achieved in low-intensity earthquakes. When the energy coming out with the earthquake exceeds the elastic limit of the structure, the elements of the structure typically bends or breaks. In other words, in this kind of situation a third term $E_h$ in the energy equation comes into the agenda.

$$E = E_e + E_k + E_v + E_h \tag{2.5}$$

Unfortunately, even in this present time the structures are designed by still using the $E_h$ term, and as a result, the reality that the deformation of the structural elements exceeds the elastic limits and resorts to ductility is accepted. In fact, accepting the deformations beyond elastic limits means resorting to the damping mechanism which causes permanent structural damage. This, in turn, means accepting the high cost renewal result, causing the structure to be out of service temporarily. Another disadvantage of this is the risk of total collapse of the structure in earthquakes exceeding the design earthquake input. The concept of meeting the earthquake energy with damage in the structural elements started to become an irrational approach with the advancing technology.

### *2.2. New approach- Lightening*

It is clear that the $E_h$ value must be reduced to minimize the damage. It is mentioned above that the structures, although limited, has a viscous damping capacity. In order to prove the equation, it is also possible to increase the amount of damped energy ($E_d$) as much as the storing capacity of the structure ($E_s$). Energy dissipaters installed in appropriate places on the structure increase the $E_v$ value, and in this way the need for the $E_h$, using the damage mechanism for damping, is reduced or completely removed. Apart from using the $E_e$, $E_k$, $E_h$ and the $E_v$ terms, it can be seen that another way to prove the equation is to decrease the earthquake energy (E) on the structure. For this, the seismic isolation systems are used, which ensures that earthquake effects are transmitted to the structure as mitigated with the horizontal displacement it causes. Seismic isolation systems at the same time have the damping increasing mechanisms. But as the damping capability they provide increases, their cost also increases significantly. Even if the cost is accepted, it is very difficult for them to reach high damping capacities.

By taking the foregoing into consideration, it should be concluded that the most rational approach may be obtained by resorting to all the terms in the energy equation. In other words, in practice, seismic isolation and energy dissipating should be combined in the most appropriate manner. This, in turn, means controlling the seismic response of the structure and guaranteeing the desired protection level in the direction of our desire. Seismic isolation and energy dissipating systems is the most effective tool possessed by the engineers working in the seismic zones, which limits both the load transfer and also the relative displacements between the structural elements with the desired values.

## 3. EARTHQUAKE RESPONSE ANALYSIS FOR VARIOUS ISOLATION TECHNIQUES – A CASE STUDY

Three dimensional nonlinear time history analysis is carried out with the SAP2000 program, on the basis of various seismic isolation and energy dissipating alternatives of a medium-rise structure and comparison of the results are given place to in the application example taken into consideration in this study.

In this context, a six-storey building model shown in Figure 1 is taken into consideration. The model building is analyzed in the nonlinear time domain both for fixed base situation and also by using various seismic isolation and earthquake protection alternatives such as rubber bearing, friction pendulum bearing, additional isolated story and viscous damper. Total base shear forces, maximum storey shear forces in the middle column, maximum absolute accelerations in the centre of story mass and the maximum relative storey drifts in the middle column are taken into consideration as the comparison criteria.

The building sits on a 24x16 m2 area, with 6m space in the X direction and 4m in the Y direction. The height is 3m, the thickness of the floor is 15cm on all storeys. The column cross-section used in the structure is 50x50cm, beam cross-section 30x60cm, and the live load is defined as $3kN/m^2$ for the floors on all the storeys. Total weight of the structure (the dead load + 0,3 x live load) is 18.500 kN. C25 is selected as the concrete material, and the elasticity module is taken as $30.250.000\ kN/m^2$. As nonlinear analysis is carried out, it is assumed that the structure and the seismic isolation shall behave beyond the elastic range, and the seismic load reduction factor is taken as R=1 while acceleration data is scaled.

The characteristics of the isolators and dampers used are selected from the available or producible products in the light of the information obtained from the manufacturers. While deciding about the isolator characteristics; the characteristics of the device, which subject the structure to minimal effects, while themselves are displacing within reasonable scales, with the criteria such as the base shear forces, storey shear forces, relative story drifts, are selected. Nevertheless, it must be born in mind that this is not a proper optimization, and a judgement may not be passed about these systems superiority over each other by just looking at the results. The real objective of the obtained results is not the comparison of the seismic isolation alternatives, but their comparison with the classical fixed base building shown in the first alternative.

### *3.1. Fixed-Base Building*

In the nonlinear analysis carried out; the 1. mode period of the structure is found to be 0,58 sec. in x direction and the 2. mode period as 0,52 sec. in y direction. In the analysis, the damping ratio for all modes is assumed to be 0,05.

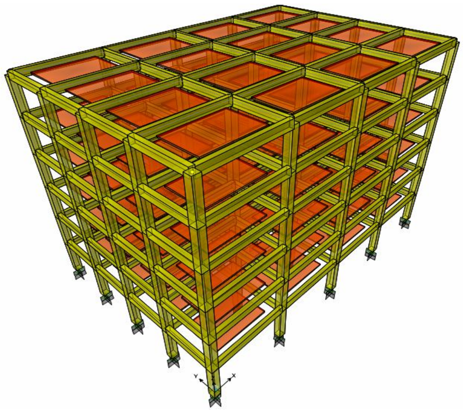

Figure 1 An aerial perspective of the structure

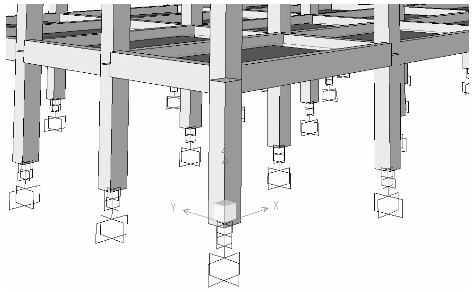

Figure 2 Nonlinear link elements

### *3.2. Alternative with Rubber Bearing*

The seismic isolators in the system are defined as Nllink components 0.5m in length placed between the fixed base and the columns (Figure 2). The parameters selected to define the utilized isolators in the SAP2000 program are as follows.
Nonlinear Link Type: Rubber, U1 Linear Effective Stiffness: 1500000 kN/m, U2 and U3 Linear Effective Stiffness: 800 kN/m, U2 and U3 Nonlinear Stiffness: 2500 kN/m, U2 and U3 Yield Strength : 80 kN, U2 and U3 Post Yield Stiffness Ratio: 0,1

All the values remaining outside the above indicated parameters are entered as zero. The reason for the effective damping value being entered as zero is its non-functionality in the nonlinear time history analysis. Damping in here occurs with the conversion of hysteresis curve under the influence of seismic loading. The modal damping values for the first 3 mode are assumed to be zero while carrying out the analysis for this damping value not to coincide with the modal damping value. In this way, the structure shall behave as if without damping, and all damping requirements shall be met by the isolators. As the damping capability of the structure, which is approximately 5%, is neglected here, it must be taken into account that the values such as the relative storey drifts, storey accelerations are slightly higher than the actual values. In the nonlinear dynamic analysis carried out, the 1.mode period of the structure is found to be 2,03 sec in the x direction and the 2. mode period as 2.01 sec in the y direction.

### *3.3. Alternative with Friction Pendulum Bearing*

Friction pendulum isolators are defined as Nllink components 0.5m in length placed between the fixed based and the columns just like in the case of rubber isolators (Figure 2). The parameters selected to define the utilized isolators in the program are as follows.
Nonlinear Link Type: Friction Isolator, U1 Linear Effective Stiffness: 15000000 kN/m, U1 Nonlinear Effective Stiffness: 15000000 kN/m, U2 and U3 Linear Effective Stiffness: 750 kN/m, U2 and U3 Nonlinear Stiffness: 15000 kN/m, U2 and U3 Friction Coefficient, Slow: 0,03, U2 and U3 Friction Coefficient, Fast: 0,05, U2 and U3 Rate Parameter: 40, U2 and U3 Radius of Sliding Surface: 2,23.
In the nonlinear dynamic analysis carried out; the 1. mode period of the structure is found to be 2,09 sec. in the x direction, and the 2. mode period is found to be 2,07 sec. in the y direction.

### *3.4. Alternative with Additional Isolated Storey*

In this alternative, an additional storey, which is isolated with rubber isolators, is added on top of the 6-storey structure. The additional storey shall behave like a tuned mass damper (TMD). Nllink components 0,2m in length are defined between the columns of the 6. storey and the columns of the additional storey (Figure 3).
The parameters selected to define the utilized isolators in the program are as follows.
Nonlinear Link Type: Rubber, U1 Linear Effective Stiffness: 1500000 kN/m, U2 and U3 Linear Effective Stiffness: 800 kN/m, U2 and U3 Nonlinear Stiffness: 1000 kN/m, U2 and U3 Yield Strength: 25 kN, U2 and U3 Post Yield Stiffness Ratio: 0,1.
In the nonlinear dynamic analysis carried out; the 1.mode period of the structure is found to be 0,91 sec in the x direction, and the 2. mode period as 0.88 sec in the y direction.

### *3.5. Alternative with Viscous Dampers*

In this alternative; total of 48 viscous dampers are placed just on the surrounding axis of the 6-storey structure (Figure 4). The parameters selected to define the utilized isolators in the program are as follows:
Nonlinear Link Type: Damper, U1 Nonlinear Stiffness: 210000 kN/m, U1 Nonlinear Damping: 7000 kN.sec/m, U1 Nonlinear Damping Exponent: 1.
In the nonlinear dynamic analysis carried out; the 1. mode period of the structure is found to be 0,58 sec. in the x direction, and the 2. mode period is found to be 0,52 sec. in the y direction.

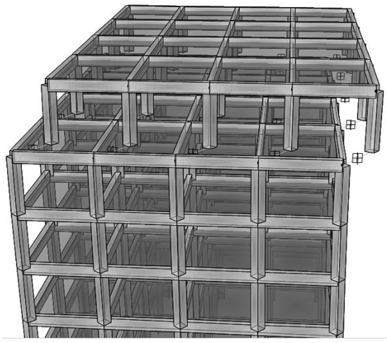

Figure 3 Additional isolated story

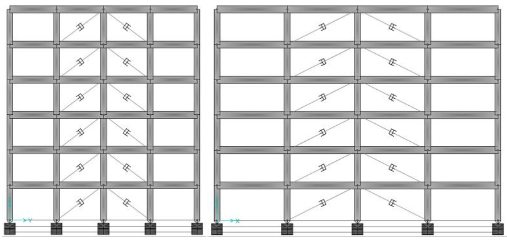

Figure 4 Viscous dampers

### *3.6. Evaluation and Conclusion*

In this section; the results obtained from the analysis are examined within the framework of the previously determined comparison criteria. The natural period of the structure being 0,58 in the fixed base situation is increased to 2 sec. level in the systems containing base isolators. When the storey shear, relative drift and acceleration values are examined, it is seen that this value is adequate for the structure being completely removed from the resonance range of the earthquake. Whereas, in the additional isolated storey alternative, the natural period is obtained as 0,9 sec. It is seen that the alternative containing viscous dampers did not have that much influence on the natural period. The weaker, y direction of the structure subjected to larger force, acceleration and deformation effects even though affected by the relatively weaker component of the earthquake. As it can be seen when the acceleration spectrum of the earthquake is examined, another reason for this is that in the fixed base situation, while a sudden drop is observed in the spectral acceleration value corresponding to natural period value of 0,58 in the longer (x) direction of the structure, the spectral acceleration is close to maximum in y direction just for this period value.

The target period for the rubber and friction pendulum systems is selected as 2 sec. corresponding to the low spectral acceleration values in the acceleration spectrum in both directions. While various isolator values are tried to reach this desired period value, it is observed that when the isolators, having 1,5sec. natural period value, are used the structure is subjected to base shear forces and relative storey drifts in x direction, which are exceeding also the fixed base situation. It is found that the reason for this is the high and sudden increase observed in the spectral acceleration value corresponding to 1,5 sec. period in the acceleration spectrum in the x direction.

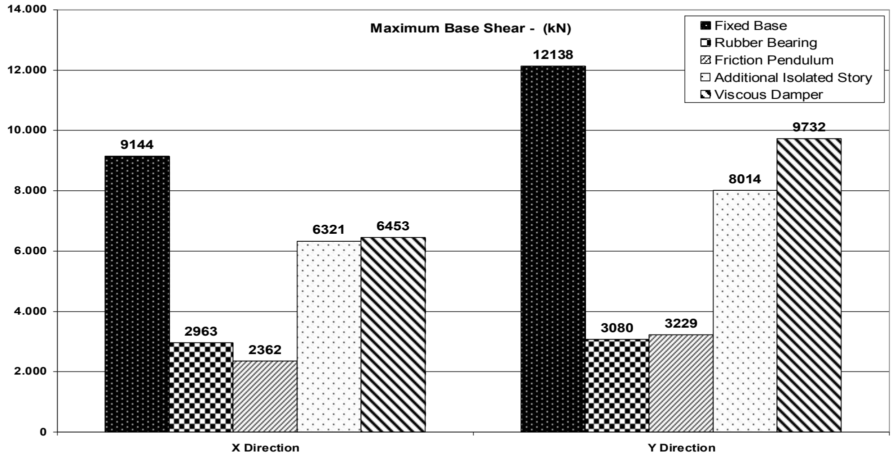


Figure 5 Maximum base shear – x and y directions

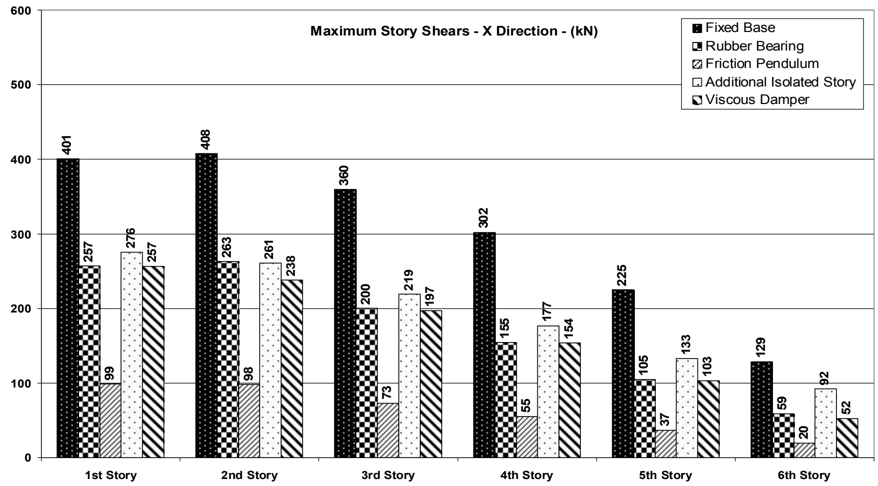


Figure 6 Maximum story shears – x direction

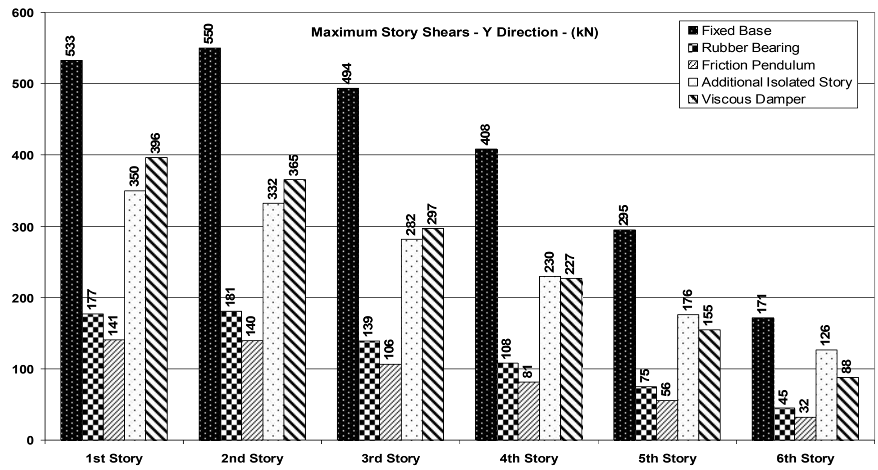


Figure 7 Maximum story shears – y direction

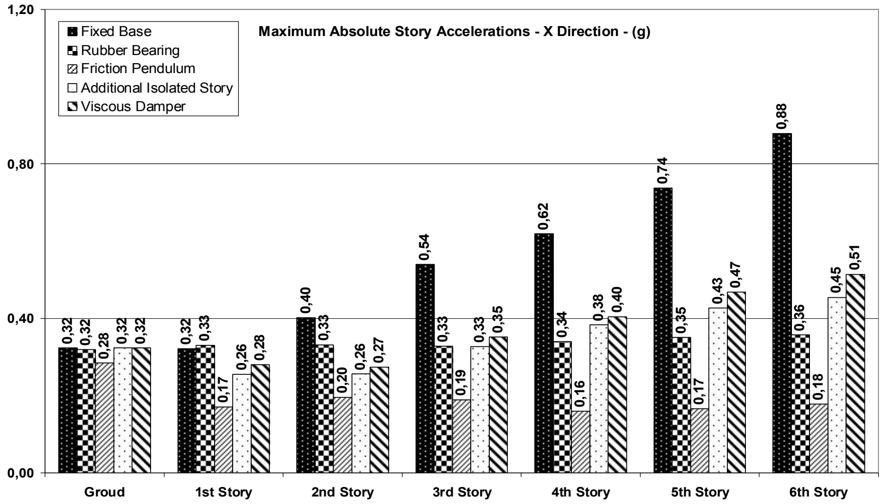


Figure 8 Maximum absolute story accelerations – x direction

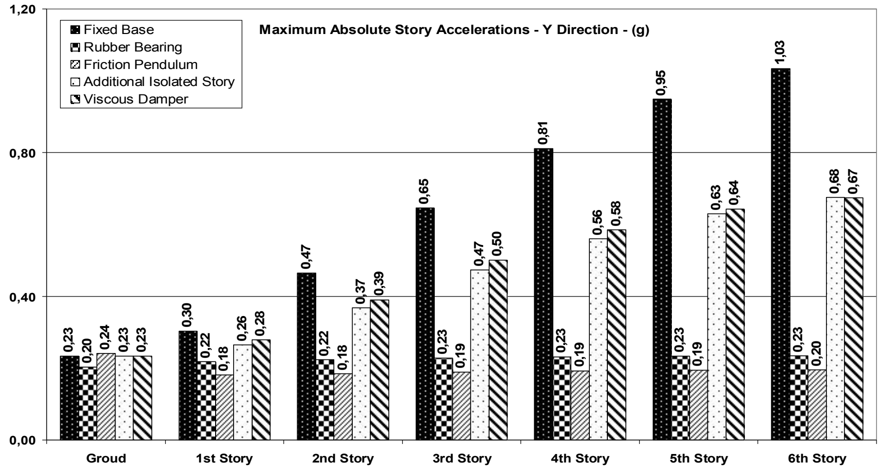


Figure 9 Maximum absolute story accelerations – y direction

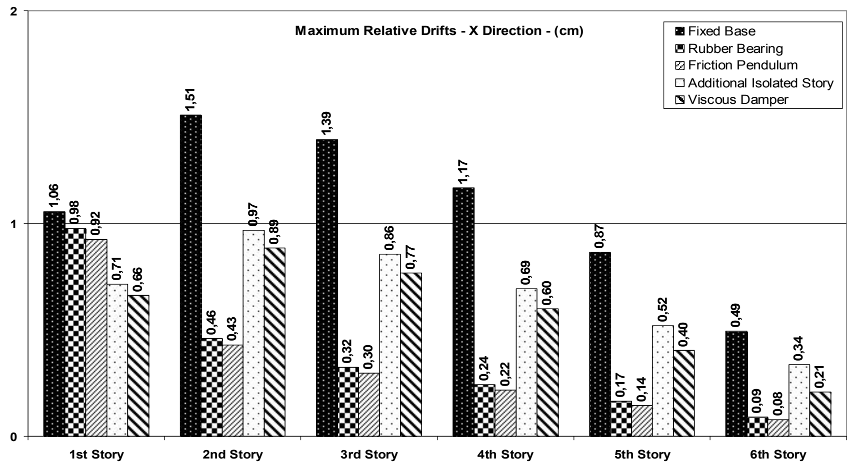


Figure 10 Maximum relative drifts – x direction

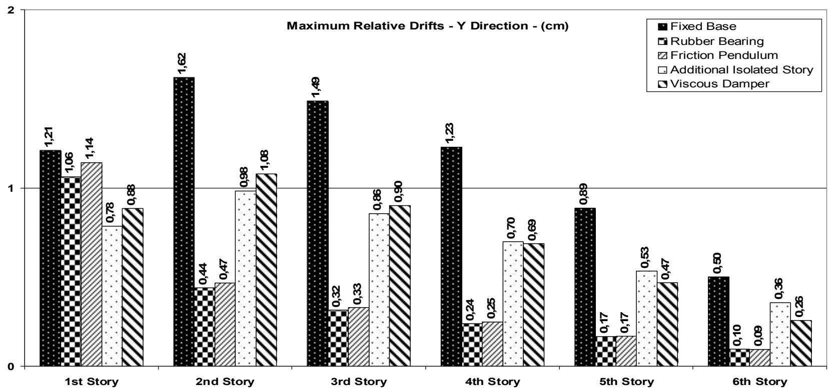


Figure 11 Maximum relative drifts – y direction

In the base shear forces, the results of the rubber and friction pendulum alternatives are very close to each other, and they provided approximately 71% reduction in the x direction and 74% reduction in the y direction. This reduction in the forces indicates that the performance of the base isolation under the influence of earthquake is extremely good. In the additional isolated storey alternative, the base shear force is reduced by 32% on average. When the reduction in the other effects are taken into account, it can be concluded that story isolation may also be considered as a strengthening alternative, as in the case of base isolation, when the characteristics of the structure allow this. Gaining an extra storey in the structure as a result of this strengthening is a situation reducing the cost of strengthening, and even making it profitable. When the storey accelerations are examined; it is seen that while high acceleration values reaching 1.0 g level are encountered while moving up to the higher storeys in the fixed base situation, whereas in the base isolator situations the acceleration values on the basis of storeys do not change that much, and remain as fixed at rather low values. An acceleration value being low is very important especially for the protection of the valuable and sensitive content of the structure. It is seen that significant reductions in the accelerations are also achieved with the additional storey and viscous damping alternatives, even if the acceleration value does not remain fixed in all the storeys. It is seen that in all alternatives, apart from the first floor, the relative storey drifts is significantly reduced especially in the fixed-base alternative. This situation indicates that the superstructure exhibits behaviour close to rigid body behaviour in base insulation. The reason for the reduction appearing low in the first floor is that when the analysis is carried out while the modal damping ratio for all modes is taken as 0.05 in fixed base alternative, the damping ratio is taken as zero for first three modes in all the other alternatives. Thus, in all alternatives, other than the fixed base alternative, the natural damping capability of the structures, which is approximately 5%, is neglected and the damping behaviour is left almost as totally depending on the behaviour of the seimic protection devices. For this reason, it must be known that in reality, with the contribution of the natural damping of the structures, the relative storey drift, acceleration and shear force values of the structures are slightly lower than the values given in the table in all the alternatives containing seismic protection devices.

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## REFERENCES

Ozpalanlar, G. (2004). Seismic Isolation and Energy Dissipating Systems in Earthquake Resistant Structural Design, *MSc. Thesis, Institute of Science and Technology, Istanbul Technical University, Istanbul, Turkey.*
Torunbalci, N. (2004). Seismic Isolation and Energy Dissipating Systems in Earthquake Resistant Design, *13th world conference on earthquake engineering, 13WCEE, Paper Id:3273, Vancouver, Canada*
Torunbalci, N. (2003). Earthquake Protective Systems in Civil Engineering Structures - Evolution and Application, *4th International Conference on Earthquake Resistant Engineering Structures ERES IV, 328-332, Ancona Italy.*