MAY 2017 M.Sc. in Civil Engineering AYAD HAMZAH MEJBEL AL-AMEERI

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EARTHQUAKE ANALYSIS OF LEAD CORE RUBBER BEARING ISOLATED STEEL BUILDINGS

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BY

AYAD HAMZAH MEJBEL AL-AMEERI

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Earthquake Analysis of Lead Core Rubber Bearing Isolated Steel Buildings

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Assoc. Prof. Dr. Esra METE GÜNEYİSİ

by

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This is to certify that we have read this thesis and that in our consensus opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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Ayad Hamzah Mejbel AL-AMEERI

ABSTRACT

EARTHQUAKE ANALYSIS OF LEAD CORE RUBBER BEARING ISOLATED STEEL BUILDINGS

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The safety and damage control are the key parameters in the philosophy of earthquake resistant design. To protect the structures, the utilization of base isolation is one of the economical and practical solutions and it mitigates the seismic load by providing both lateral flexibility and energy dissipation. In this study, the effect of using lead core rubber bearing isolator on the seismic performance of the mid and high rise buildings were investigated. For this, 5, 10, and 15 story steel frame buildings were used as the case study. These buildings had the same plan with 6 bays of 6 m span in x-direction and 3 bays of 6 m, 4 m and 6 m spans in y-direction. These spans of the buildings were selected to indicate the typical residential building spans. Modeling and time history analysis of the base isolated and fixed based cases were performed by means of a finite element program. Three earthquake ground motion records were used in the earthquake analysis. The characteristics in terms of relative displacement, drift ratio and time history variation of some response parameters were studied. From analytical results, it was observed a significant reduction in the seismic response of the isolated buildings as compared to the fixed base cases.

Keywords: Seismic load, Lead rubber bearing, Base isolation, Steel building, Time history analysis.

ÖZET

KURŞUN ÇEKİRDEKLİ KAUÇUK İZOLATÖRLÜ ÇELİK BİNALARIN DEPREM ANALİZİ

AL-AMEERI, AYAD HAMZAH MEJBEL
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Depreme dayanıklı yapı tasarımı konseptinde güvenlik ve hasar kontrolü anahtar parametrelerdir. Yapıyı korumak için, taban izolasyonunun kullanımı ekonomik ve pratik çözümlerden biridir. Taban izolatörleri yanal esneklik ve enerji sönümlemesi sağlayarak yapının sismik yükünü azaltırlar. Bu çalışmada, kurşun çekirdekli kauçuk izolatör kullanımının orta ve yüksek katlı binaların sismik performansına etkisi araştırılmıştır. Bunun için 5, 10, ve 15 katlı çelik çerçeve binalar kullanılmıştır. Binalar aynı kat planına sahip, x yönünde 6 m'lik 6 açıklıktan, y yönünde ise 6, 4, ve 6 m'lik 3 açıklıktan oluşmaktadır. Binanın bu açıklıkları tipik konut yapılarının açıklıklarını yansıtacak şekilde seçilmiştir. Ankastre mesnetli ve taban izolatörlü yapıların modellenmesi ve zaman tanım alanındaki analizleri sonlu elemanlar programı ile gerçekleştirilmiştir. Deprem analizinde üç deprem yer hareketi kaydı kullanılmıştır. Göreceli yer değiştirme, ötelenme oranı ve bazı tepki parametrelerinin zamana bağlı değişimi gibi özellikler incelenmiştir. Analitik sonuçlardan, ankastre mesnetli durumlara kıyasla, izolasyonlu binaların sismik tepkisinde belirgin bir azalma olduğu görülmüştür.

Anahtar Kelimeler: Deprem yükü, Kurşun kauçuk mesnet, Taban izolasyonu, Çelik bina, Zaman tanım alanında analiz.

To My Family

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LIST OF SYMBOLS / ABBREVIATION

AASHTO	American Association of State Highway and Transportation Officials
A_o	Acceleration coefficient
ASCE	American Society of Civil Engineers
B	Damping factor
C	Corralitos earthquake
D	Displacement (cm)
DOF	Degree of freedom
E	Energy dissipated per cycle at the displacement D
F	Yield strength (kN/m^2)
FBI-3D	Full base isolation-three dimension
FPS	Friction pendulum system
GLIS	National working group on seismic isolation
K_d	Post-elastic stiffness (kN/m)
K_{eff}	Effective stiffness (kN/m)
K_u	Pre-elastic stiffness (kN/m)
LRB	Lead rubber bearing
MRPRA	Malaysian Rubber Producers' Research Association
N	Northridge earthquake

Q_d	Characteristic strength (kN)
Q_y	Yield force (kN)
RB	Rubber Bearing
Si	Site coefficient for isolated structures
SM	Santa Monica earthquake
T_{eff}	Effective period (s)
UBC	Uniform Building Code
Y	The yield displacement (cm)
β_{eff}	Effective damping ratio
γ	Shear strain
ε	Tensile strain

CHAPTER 1

INTRODUCTION

1.1 General

The earthquake is a sudden jolt or the Earth's crust move, which occur naturally in or below ground level, where the rocks are exposed to extreme stress and sudden fracture, these motions called the earthquake. Vibration of structures due to impact of ground motion (earthquake), causes an inertia force, which proportionate to the product of the mass of the building and the acceleration of ground. Whenever acceleration of ground increased, strength building should be increased, to avoid the damage to the structure, But, not practical to continue to heighten the strength of the building indefinitely, especially in some high seismic zones may exceed the force that causing accelerated in the building, to one or two times the acceleration of gravity. Therefore, measures have been developed to control the movement of the building during an earthquake, one of these measures is base isolation. Base isolation is a technical design founded on the assumption that a structure can be separated from horizontal movement due to the earthquake motions so that levels of force and acceleration in the structure will be significantly reduced, while at the same time it supports the vertical weight of the building (Griffith et al., 1988).

The principle of isolating a structural system from ground vibrations has been understood for many years, and numerous successful implementations exist in which bridges or buildings are mounted on resilient bearings. However, it is only in the last years of the last century that designers have developed sufficient confidence to incorporate isolation as the primary means of protecting structures from earthquake-generated strong ground motion**.** Greater understanding of the nature of strong seismic ground movements, and the ability to model structural systems using computers, undoubtedly have benefitted the design process, but the most significant recent advances have been prompted by the development of a range of various isolator devices. These include different groups of the simple rubber blocks, steel torsional and flexural beams, lead extrusion elements and steel plates interlayered with elastomeric materials (Buckle and Mayes, 1990).

The application of base isolation to address the problem of providing earthquake resistance to structural systems is a radical departure from the traditional approaches used by structural engineers. In conventional fixed-base design, efforts to strengthen the structural system to provide superior seismic performance lead to a stiffer structure, and thus will add more resistance and more safety to the structure and its contents. The building has a fixed base tends to amplify the ground motion. In order to reduce this amplification, the structural system must either be very rigid or provide high levels of damping. At best, the rigidity leads to the contents of the building, which suffers from the accelerated ground motion that may be too high for sensitive internal equipment and content. The alternative of providing high levels of damping into the system generally leads to damage of the structural system or to structural forms. Isolation allows the engineer to design a system that can function without damping, yet protects the building and its contents with relatively simple and low cost structural systems. The concept has been long in gestation, but is now being used enthusiastically in many countries. At the present time, there are several types of isolation systems in use, many variants of existing systems are being developed, and new systems are being proposed and tried (Kelly,1993).

The elastomeric bearing, as one of the types of the base isolation, is particularly suitable for isolation applications because period shift and added flexibility can be attained by increasing the thickness of the bearing. While, the vertical flexibility is not desirable, so the vertical rigidity is maintained in an elastomeric bearing by sandwiching steel shims between each rubber layer. The steel shims, which are bonded to each layer of rubber, constrain lateral deformation of the rubber resulting in vertical stiffness several hundred times the lateral stiffness (Kelly et al., 1987).

The use of base isolation for the seismic protection of buildings and other structures has become the subject of considerable interest in the structural engineering profession since it offers a method of seismic design which could both reduce costs and increase safety. It can reduce costs by permitting the use of simpler framing systems such as braced steel frames or ordinary reinforced concrete frames rather than moment resisting steel frames or ductile concrete frames. It may increase the degree of protection offered to the structure by allowing the structure to be designed elastically for any earthquake that may be anticipated at the site within the lifetime of the structure and would allow the structure to be designed for an extreme earthquake with reduced ductility demand (and hence reduced damage) (Kelly et al., 1986).

Strong earthquakes that have occurred in the last decades, especially in 1989 Loma Prieta and the Northridge earthquake in 1994 and the Kobe earthquake in 1995, which happened in Japan, when they happen in heavily populated areas, caused great loss of life and property. In addition to the structures which collapse those left standing may have been weakened after the earthquake or may have had their contents totally destroyed. The damage from an earthquake is caused mainly by the horizontal ground motion, which is amplified by the vibratory response of the building. Standard methods of building for earthquake protection have concentrated on strengthening buildings to resist these horizontal forces. However, when the structure of the building is strengthened it may increase the degree of amplification of the ground motion and while the building may be saved in this way, its contents may be more hardly damaged and the risk to occupants increased. Over the years it has been the development of many of the designs of buildings prone to earthquakes and the use of technologies to reduce the impact of the earthquake on buildings, the mitigation of the severity of ground motion on buildings is one of the most popular topics in the field of civil engineering, where is a pull Station for many of the engineers, researchers in all countries of the world (Kelly and Hodder, 1981).

Earthquakes do not kill people, but the buildings do, so the first responsibility of the structural engineer (designer) is extracting information from past experiences and consider all the potential risks that might be exposed to the structure in the future for the purpose of setting the security design of the structure. A computer component and software has been developed for the analysis and display the results accurately. Research has been reached in civil engineering to the prospect of a very wide by helping these technological developments in the computer to decrease a lot of time and effort, as building codes that structures be designed to withstand a certain intensity of accelerating commensurate with ground motion intensity depending on the seismic endanger. Where, the usage of ductility, for dispersion of the energy resulting from the earthquakes to the structure, gave the designers sufficient space for judging the performance of the structures and monitoring the same while designing. The design of the structures based on the execution under the loading may well be anticipated by modelling the structure mathematically. This can be proficiently done by any of the software accessible in the market, for structural modelling, analysis and design. The forecast of the execution of a structure, designed for a specified pattern of loadings and level of safety holds good importance for the practicing structural design engineer. Although analytical finite element procedures have become highly developed in recent years, there is still a great need for experimental testing of structural elements and sub assemblages, to know their behavior when exposed to severe seismic forces. Aspects of the behavior of interest in seismic design are stiffness, strength, ductility, energy dissipation, change of these characteristics and damage with cyclic loading, and retrofitting and repair ability of undamaged and damaged structures. Most of these aspects cannot be determined with complete confidence by analytical procedures, and need to be assessed by experimental methods (Park, 1992).

1.2 Importance of seismic analysis

The expectation of the response of a structure to a particular type of loading is very importance for the design of the structure. Essentially the codes and preceding experiences supply us with a lot of information regarding the type of loads and their concentration for various types of structures and the site conditions. The analysis procedure to be adopted simply depends upon the engineers' choice as per the exactness of the work required. Moreover, it can regard the nonlinear time history analysis as the most accurate method of seismic prediction and performance evaluation of structures. Although, this method requires the selection of an appropriate set of ground motion, detailed site conditions and also a numerical tool to handle the analysis of the data, where, still it is regarded as the most detailed analysis and highly accurate analysis method (Pasticier et al., 2008).

1.3 Purpose of the Thesis

The main goal of this thesis is to observe the seismic performance of the steel frames equipped with base isolation. As a base isolation device, lead core rubber bearing isolators were used. The steel buildings were examples of mid and high rise structures of 5 to 15 stories. In the dynamic analysis, different ground motions have been employed. The response of the case study structures were evaluated comparatively.

1.4 Scope of the thesis

In this thesis, the whole work is demonstrated via five chapters:

Chapter 1- Introduction: This chapter is dedicated to the presentation of the research topic and the identification of the overall range and specific objectives. Knowledge and objectives of thesis were introduced.

Chapter 2- Literature Review: The previous studies based on the scope of the research were presented and obtained. An investigation of seismic analysis of base-isolated steel frame buildings were summarized.

Chapter 3- Case Study: In this chapter, type of frame system and properties and details of building frame that used in this study is offered. Moreover, the methodology used in the design and analysis of the steel frame was given in detail in this chapter.

Chapter 4- Results and Discussion: Findings which obtained from the nonlinear time history as a dynamic analysis for the steel frame were given. Discussion on the findings of the analysis was described in this chapter.

Chapter 5- Conclusions: The conclusions built on the analytical findings were summarized.

CHAPTER 2

LITERATURE REVIEW

2.1 Background

Many mechanisms have been invented over the last century to try to achieve the goal of uncoupling the building from the damaging action of an earthquake, for example, rollers, balls, cables, rocking columns, as well as sand. Buildings have been built on balls, including a building in Sevastopol, Ukraine, and five-story school in Mexico City. At least one building, a four-story dormitory for the State Seismological Observatory in Beijing, has been built on a sand layer between the building and the foundation specifically designed to slip in the event of an earthquake. The reference is almost certainly to the John Milne, who was a professor of mining engineering in Tokyo in the years 1876 through 1895. During this period Milne became very interested in earthquake phenomena, and he devised and improved a number of seismic scopes and seismographs. Milne carried out pioneering research in seismology, so much so that he is often referred to as the "Father of modern Seismology". He also gave much thought to the design of buildings in seismically active areas and published rules for earthquake resistant construction that are still valid today. Whereas at the University of Tokyo, he built an example of an isolated building. The structure was built on balls in "cast-iron plates with saucer-like edges on the heads of the piles. On top of the balls and attached to the buildings are cast-iron plates little concave." The building was instrumented and apparently experienced earthquake movement. In 1885 he described this experiment in a report to the British Association for the Advancement of Science. Apparently he was not completely satisfied with the performance of his building under wind load, so he changed the isolation system. The first balls had been 10-inch in diameter; 8-inch balls were tried, then 1-inch balls. Eventually, the design of the house settled on the piers of cast iron with a diameter 0.25 inch. By this means the building became stable against wind loads. The final design was evidently successful under the actual earthquake action (Naeim and Kelly, 1999).

Freyssinet (1954) is the first to proposed the idea of reinforcing rubber blocks by thin steel plates. He considered that the vertical strength of the rubber pad was inversely proportional to the thickness, while the horizontal flexibility was directly proportional to it. He was invented of the reinforced rubber pad for the need to accommodate the shrinkage of the deck due to creep and pre-stressed load, while sustaining the weight of a pre-stressed bridge deck.

Westermo and Udwadia (1983) studied the periodic response of a linear oscillator on a coulomb friction sliding interface, these study consider a theoretical analysis of the dynamics of structures on sliding systems subjected to harmonic input or to earthquake input, as an example to the representation of a base-isolated building. Contrary to the general perception that friction will always reduce the response, they found that the response may be larger than that for the same fixed-base model and that the single degree of freedom model had subharmonic resonance frequencies generated by the sliding interface. They have been noticed that The assumption of coulomb friction is generally used in these theoretical analyses but is unlikely to be an accurate representation of real behavior.

Betbeder et al. (1992) have made a study for ensuring the correct operation of the ensemble of the pads by avoiding the creeping of the pad units, except in the case of controlled sliding plates; when these exist (the elastomer pads must remain compressed), that in the case of pads including a sliding system the movable component can escape from the plate, that the ensemble of the block consisting of the superstructure above the pads does not impart a shock to neighboring infrastructures and superstructures. And that the fluid lines connecting the block on the pads to the exterior can be damaged due to displacements of the block. The study included the dynamic response of the system has to be studied following the methods stated in the section basic to all the recommendations (spectral modal method or chronological analysis), when the behavior of the system cannot be represented linearly, which is, in particular, the case when sliding plates are used, a nonlinear chronological analysis must be used. It has been taking into account in making the calculations the following hypotheses; first, the building must have a sufficiently uniform lateral resistance and the vertical loads must be transmitted directly from the columns and the supporting walls to the pads, to avoid deformations which invalidate the hypothesis that the superstructure cannot be deformed. Second, the vertical and the rotation rocking stiffness of the pads and the underlying foundation are high enough to prevent the horizontal acceleration of the masses from affecting the rocking. And third in order to have a pure translation, the superstructure must not have too much deformation on bending, when subjected to horizontal acceleration. The conclusion was the earthquake resistant design of buildings have so far been mostly based on experience, it may therefore look premature to make an attempt towards regulating base isolated structures for which experience from actual earthquakes is currently very limited, the discussions within the working group have shown that the key issues for a safe a seismic design of such structures were reasonably well identified, will provide useful guidance for designers.

Shibata and Aoyagi (1992) has been managing the verification test program of seismic isolation systems. This research program mainly focuses its target on the establishment of the horizontal base isolation technologies of reactor buildings, in which a several large scaled tests such as the failure modes tests of various isolators, the shake table tests of various types of isolated structures have been carried out. The primary objectives of these tests are to establish the design criteria of isolators and isolated structures as well as to assure their long term integrity. Furthermore, earthquake motion with long period components has been studied in order to prepare an appropriate method to determine design earthquake motions.

Tian and his cooperators have done some research work in this field. In 1982, they suggested a method to analyses a large structure with artificial damping (Tian et al., 1982) and a method to calculate the frictional base isolation problem. In 1984, they developed a method to calculate the stochastic response of a structure with frictional joints (Tian, et al. 1984). In 1986, Prof. Tian in cooperation with Hong Kong University made some analyses and did experiments on infilled frame models with sliding bases (Tian, et al.1986; 1987). In 1987 they suggested a method for the vibration isolation of a super-structure of an ocean platform. Model test results showed that the peak response can be reduced about 5% by using a sliding base isolation with heavy damping. They also developed a method for the dynamic analysis of large structure with locally strong nonlinear elements by applying the impedance method and incremental harmonic balance method. Through experiments and analyses, they suggested that the wire-rope isolator may be used as a mechanical fuse in seismic design instead of the dry friction device. It has the advantages of easy to repair and easy to be controlled during and after an earthquake excitation (Tian et al., 1987; 1989; 1990; and 1991).

Kelly presented a study in 1992 including a new types of isolation systems have been proposed that are based in some way or another on sliding systems. Sliding elements and sliding isolation systems have been tested in the bearing testing machines and in model systems used in shake table testing. As compared to elastomeric systems, sliding systems have both a number of advantages as well as some drawbacks. The major advantage is cost. Sliders are widely used for both bridges and to reduce shrinkage and thermal stresses in large reinforced concrete structures; thus, the manufacturing base for sliding elements is very wide. Many companies make sliding bearings and the industry is highly competitive. Thus, the cost of a sliding bearing is low compared to that of an elastomeric bearing. The cost factor between the two depends on detailing and size, but might be of the order of 1/2 to 1/3. The other advantage the sliding bearing has is its low height as compared to an elastomeric bearing. The sliding bearings can be combined with elastomeric bearings. The use of sliders gives a system with a long period without running the risk of instability in the elastomeric bearings. The rubber bearings control the displacement by giving a centering section; additionally, they control torsion and if the displacements exceed the design level they produce stiffening action (Kelly, 1992).

This type of system was also studied experimentally on the shake table and its performance was excellent. The system of this type was used in the seismic rehabilitation of a university of Nevada building, the Mackay School of Mines in Reno, Nevada (Way and Howard, 1990). The study included three retrofit projects under construction; two using lead-rubber bearings, and as mentioned above, one using the combined high-damping rubber and slider system. The rubber compound used in the bearings is designated KL401, which is a high-stiffness, high-damping rubber with around 31% carbon filler. The rubber has a shear modulus of around 0.86 MPa at 100% shear strain and an equivalent viscous-damping factor of around 15%. The bearings are very flat with a width that is about four times the height between the end plates. The shape factor is 30, which for these bearings is very high. Four bearings were tested under horizontal shear in displacement controlled cycles from ±5% up to a maximum of ±350%. The test program was identical for all bearings with one variation, the vertical pressure was different for each bearing and ranged from zero pressure through 3.45, 6.90, and 10.34 MPa. After the cyclic tests, each bearing was loaded monotonically to failure at the same level of vertical load. The effective stiffness and the equivalent viscous damping are the characteristics of most interest to be determined from the dynamic tests. They have been shown to be capable of extremely large shear strains before failure even under high levels of vertical pressure. Additionally, because the failure mechanism is only slightly affected by pressure, and the stiffness is unaffected by pressure while the damping is increased by pressure, these unique characteristics can be used in the design process, leading to the implementation of smaller isolators than those currently in use.

Seidensticker et al. (1992) performed a number of tests of elastomeric seismic isolation bearings. These tests were conducted as part of the U.S. Department of Energy (DOE) program to develop seismic isolation technology for use in nuclear facilities, and also as part of a joint U.S./Japanese program to study seismic isolation. The goals of these tests are to determine the performance characteristics of isolator bearings under a wide range of loadings, to determine failure modes and to establish safety margins. During the course of conducting these tests, three types of elastomeric bearings were tested. The results of these tests are presented along with conclusions relating to bearing design and manufacture, acceptance testing and margins of safety against failure. Three types of high-damping rubber bearings, each procured from a different manufacturer, have been tested: (1) high shape factor of high shear modulus bearings; (2) medium shape factor of high shear modulus bearings; and (3) medium shape factor of low shear modulus bearings. For example, Figure 2.1 shows the configuration of the Sendai bearing, while Figure 2.2 illustrates typical steel laminated elastomeric bearing. As a summary of the study above the high performance characteristics of the high damping-high and low shear modulus elastomeric bearings. The tests have shown that these bearings are capable of experiencing extremely large shear strains (several times the design shear strain level) before failure occurs. Failure mechanisms of these bearings are strongly influenced by the quality of the bond between the steel plates and shims and rubber layers. Bearings tested in fatigue at 150% shear strain sustained up to 1120 cycles before failing. This is roughly equivalent to about 30 minutes of extremely strong ground shaking. These results are more than satisfactory when considering that no earthquake will generate so many cycles with such large displacements.

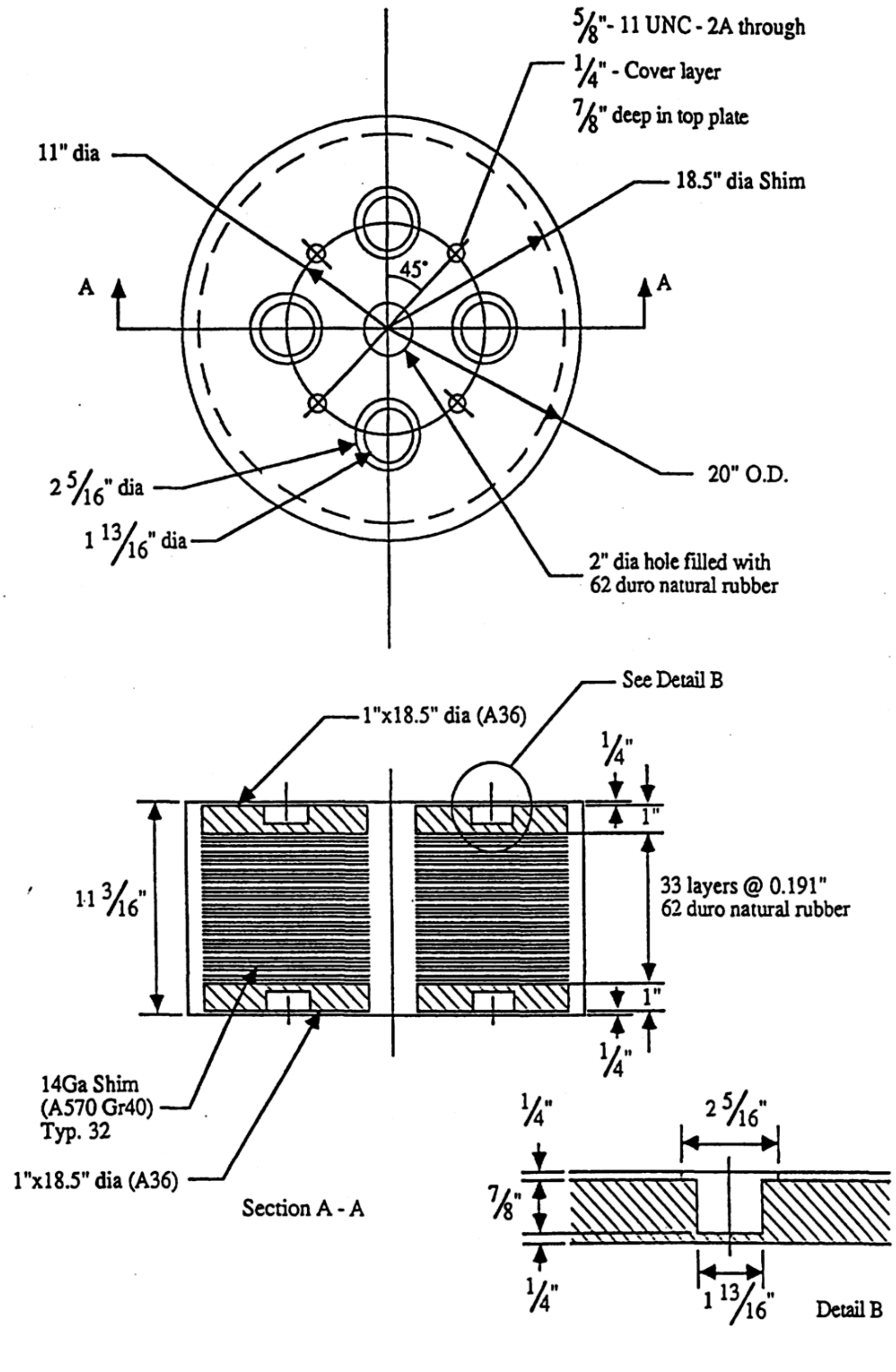


Figure 2.1 Design detail for Sendai bearing (Seidensticker et al., 1992)

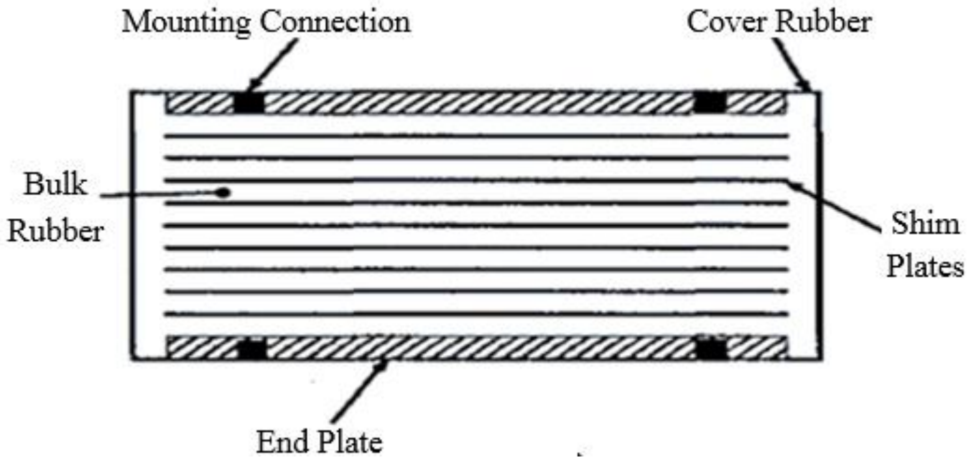


Figure 2.2 Typical steel-laminated elastomer seismic isolation bearing (Kulak, 1992)

Malhotra (1997) presented a study to isolate the vertical cylindrical liquid-storage tanks, he proposed using vertically soft rubber bearings to support the tank walls, in addition to supporting a soil bed by the base plate. The flexibility of this isolated system was drawn on rocking and uplifting of the base, and the energy-dissipation capacity was derived from the base - plate yielding, soil damping, and hysteretic rubber damping. The series of nonlinear hysteretic analysis has been done for two selected loading-unloading cycles. The results showed the isolation system was soft in the vertical direction, this method is also suitable for seismic resistance and especially for concrete wall tanks which supported directly on the soil. Moreover, the numerical results showed that this method significantly reduces the overturning base moments that transmitted to the foundation and the axial compressive stresses generated in the tank wall.

Kim (1999) submitted a study about the effective stiffness of base isolation system to reduce both the large displacement and acceleration response of the structure efficiently. Also included these studied the relationships between displacement responses of the structure and acceleration under several earthquakes, where are investigated in several horizontal stiffness of the base isolation system to determine the effective stiffness of this system. An example is a five-storey steel frame building has been used in this study as a model, input motions used in the structural analysis are El Centro, Taft, Mexico, the San Fernando 1971 Pacoima Dam, and artificially generated earthquakes. The results show that the isolation system is very effective at reducing the seismic response of the structure for all earthquakes mentioned above except the Mexico earthquake which contains long periods, where the isolation system was not effective for reducing the seismic response. Also, he noted that the effective horizontal stiffness of the support-isolated structure is equivalent to the period of 1.4 seconds, which is the natural period for simultaneously small acceleration and displacement responses. Generally, the relative displacement response of the storey to the base of the superstructure is very small. In this study, the results can be used to determine the effective stiffness of the base isolation system.

Ramallo et al. (2002) searched a using of technology was named a Smart, which means base isolation strategy. It is composed of conventional low-damping elastomeric bearings and smart as a damper can be controlled. To demonstrate the advantages of this system, a comparison between the proposed smart base isolation system and lead-rubber bearing isolation system, has been carried out. The several historical earthquakes scaled to various magnitudes has been used to determine computed responses of structures. The model was a five-story building with base isolation has two- and six-degree-of-freedom (2DOF and 6DOF) use as a test bed in this study, in order to show the potential advantages of smart dampers and the limited performance of passive systems. Also two lead-rubber bearings were designed (LRB1and LRB2), with bearing yield force Q_y equal to 5 and 15% of the building weight, respectively. The conclusions from this study were that a smart damper system can provide protection from a different earthquakes motion, more than the design of lead rubber bearing. Both of a smart damper and lead rubber systems can be reduce base drift, but, smart damper sometimes was better, while structural accelerations, inter-story drifts, and base shears have been reduced by both types of isolation equally.

Kilar and Koren (2008) studied the use of a simplified nonlinear method for seismic analysis and performance evaluation (N2 method) for analysis of base isolated structures. In this study the N2 method is applied for analysis of a fixed base and base isolated simple four story frame building. It has been investigated in two different groups of base isolation devices: a rubber bearing and a lead rubber bearing as a base isolation system. For each system used three different damping and a soft, normal and hard rubber stiffness. The study has resulted how we can determine base displacement and top relative displacement for different bearing stiffness and selected damping. Also, they found an important note that the capacity curves are elastic only for RB isolators and nonlinear for LRB isolators. In this way a target base displacement for any type of nonlinear behavior of bearings could be obtained. The analysis of the test structure clearly shows how the stiffer isolators with higher damping give smaller target base displacements as softer ones with lower damping. It can be also seen that the relative displacements of the superstructure are smaller if the softer isolators are used. The study was shown that N2 method might be a valuable tool for design, analysis and investigation of behavior of base isolated buildings with different seismic devices.

Yuanqing et al. (2011) studied using of lead rubber bearing (LRB) as a base isolation to isolated a piers of the bridge. Dynamic analysis-time history method has been carried out with seven different earthquake function, in order to determine the seismic response of piers with and without isolation. Also, three types of lead rubber were designed depending on the isolation ratio of the moment at the bottom of the pier, and parameters of base isolation were divided into five levels (F=1-5E+05), according to yield stiffness. The results showed that, when yield strength at a second level and above (F>2E+05), the seismic response was increased, while it was decreased when yield strength at first level (F<2+05E). Generally, the conclusion from this study was that the mechanical parameters of LRB had more effected on the isolation ratio of the moment at the bottom of the pier.

Farissi (2013) presented a study about design and analysis of base isolated structure, he used lead rubber bearing and high damping rubber bearing, as a base isolation for 20 story building, and he combination of those two bearings. The main focus of this study is the comparison of the response between the structure with a fixed base and the base isolated structure. Moreover, it has been a comparison of the response generated by each type of a base isolation system. The response which is compared included, base shear, natural vibration period, and hysteretic curve of base isolation. He was concluding from this study that, fundamental period of structure with fixed base is shorter than a structure with isolated base, also, the base shear value with fixed base is greater than the structure with base isolation, comforter this a caused to effective of shifting period (the longest periods for structure with base isolation it caused a smaller value of the base shear). Moreover, the building with high damping rubber bearing as a base isolation system can absorb the energy of earthquake most effectively.

Mkrtychev et al. (2014) studied abut effective of lead rubber bearing as a seismic isolation system with many building under different earthquake motions. Non-linear analysis with and without base isolation has been carried out, for building 5, 9, and 16 story of ferro-concrete. The results from the analysis showed that a reduction of seismic loads on the building depending on its height, to 5.5 times, while, the relative displacement was decreased to 8.5 times, moreover, the absolute acceleration has been reduced to 2.8 times, compared to a fixed-base building.

Nassani and Abdulmajeed (2015) presented a studied included the using of base isolation as a utilized advanced method for seismic resistance. Two different structures have been presented, symmetrical and non-symmetrical 5-story reinforced concrete school buildings in order to verify the effect of base isolation systems, where, the comparison between fixed base and base isolated has been done by using SAP2000 computer program. Moreover, they used high damping rubber as a base isolation, and time history analysis has been performed on three earthquakes: El Centro, Loma and Coyote. The results of those studied was a reduced the response of the structure, the base shear force, and story drifts by using base isolation. Where the drift ratio decreased from 0.003 with a fixed base to 0.0007 with base isolated.

Khurshid (2016) has been studied including comparison between the response of base isolated building with that of a conventionally designed earthquake resistant building, in order to predict the response of the structure during earthquake, and it's made more safety, by used The finite element software SAP2000, to analysis model consists of nine stories reinforcement concrete frame building, with use lead rubber base isolator as a base isolation. The analysis included a non-linear static pushover and non-linear time history analysis, to study the response of base isolated building as well as fixed base building. The result of his study was that the base shear has been reduced to 47% and drift ratio also reduced from 0.3% to 0.1% when used lead rubber isolator as a base isolation.

Reddy et al. (2017) worked on a study to reduce the possibility of resonance, and increase the time period of the structure, in order to better seismic performance of the building, by using two isolation system (lead rubber bearing and Friction pendulum system). Moreover, the study included a comparison between the effectiveness of fixed base and base isolated. Two buildings had been designed, the first was 5-story reinforced concrete frame, and the second was a 17-story building, in addition to the ground floor. The analysis has been done by SAP2000 computer program. The results showed that the responses of structures and the base shear were decreased when used base isolation in both types (lead rubber and friction pendulum). While the time period of both the isolated structures was increased, compared with the fixed base structure. Also the results indicated to, the story drift was reduced, while the story displacement was increased, by using the isolators. Furthermore, the results showed that the time period of the isolated building is greater than that of a building with a fixed base. Generally, the study has been proved that the use of isolated base is the best methods to isolate buildings from the impact of earthquakes.

2.2 Isolation components

Base isolation is presently a mature technology and is applied in many countries, and there are a number of isolation systems that have been well constructed. Nevertheless, the concept appears to have an irresistible attraction to inventors, and many new and different systems of isolators are proposed and patented each year. Many of these new systems will prove to be impractical and some might actually be lethal, but the number continues to increase year by year. Generally, most systems used combine either elastomeric with elastomer bearings, either natural rubber, or the sliding surface bearings Teflon and stainless steel. Also it has been proposed systems were consisting of a combine sliding bearings and elastomeric bearings (Patil and Reddy, 2012).

2.2.1 Elastomeric-based systems

Natural rubber bearings were first used against earthquake impact on constructions, in 1969 for the Pestalozzi School in Skopje, (Staudacher, 1982*)*. Where it used large rubber blocks without the steel reinforcing plates used today and compress by about 25% under the weight of the building. The bearings have a vertical stiffness that is only a few times the horizontal stiffness and the rubber is relatively un damped. Some types this bearing are added with blocks of foam glass on both sides of the rubber bearing, which aims to act as fuses to prevent movement in the structure under the wind, internal foot traffic, or low seismic input. Moreover, it has been development for elastomeric bearing by adding internal steel reinforcing plates, referred to as shims, for natural rubber bearings to increase the resistance of lateral bearing against the bulging, and to increase vertical stiffness. Laminated elastomeric bearings can be divided into low-damping or high-damping types (Kelly and Hodder, 1981).

2.2.1.1 Low-damping natural and synthetic rubber bearings

Low damping natural rubber bearings and synthetic rubber bearings have been widely used in Japan in coupling with supplementary damping devices. The elastomer was using in Japan included natural rubber, while in France neoprene has been used in different structures. The isolators have two thick steel endplates and many thin steel shims, as shown in Figure 2.3. The rubber is vulcanized and bonded to the steel in a single operation under heat and pressure in a mold. The steel shims prevent bulging of the rubber and provide a high vertical stiffness but have no effect on the horizontal stiffness, which is controlled by the low shear modulus of the elastomer (Minowa et al., 2000).

There are many merits for low damping rubber bearing are: They are simple to manufacture, the mechanical response of low damping is unaffected by rate, temperature, aging, and easy to model. the disadvantage of this isolator is that a supplementary damping system is generally needed, these supplementary systems are prone to low cycle fatigue (Kelly and Quiroz, 1992).

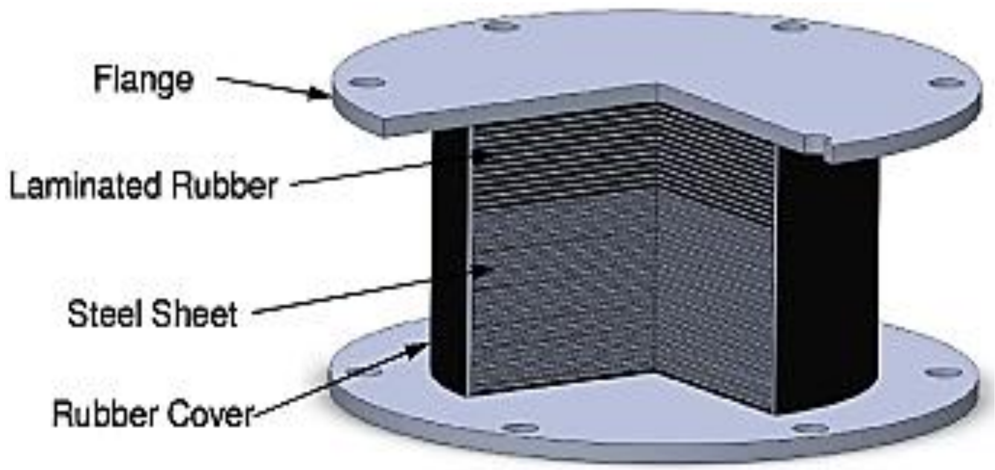


Figure 2.3 Low damping natural rubber bearing (Reddy et al., 2017)

2.2.2.2 High-damping natural and synthetic rubber systems

The relative displacement between the ground and the building is considering the control of design criterion for base isolation systems. As the reduction of the isolation frequency increasing of the relative displacement. One way of reducing the relative displacement without increasing the acceleration is to increase the effective damping in the bearings. However, rubbers both artificial and natural with high damping are subject to creep and reduced strength and it is relatively difficult to produce rubber suitable for an isolation bearing with a damping a factor greater than 0.1 which corresponds to 5% of critical equivalent viscous damping in the fundamentally isolated mode of the structure. Increasing the damping to around 10% of critical damping would improve the displacement characteristics of the isolation system while retaining low acceleration transmission. One method of increasing damping is to include in the isolation system a set of energy absorbing devices which operate on the principle of elastic-plastic cyclic deformation of mild steel. Examples of these have been tested on the shaking table by researchers Takayama, Oka, and Kato in 2004, as Figure 2.4. They concluded that, the laminated rubber bearing has the large capability for tensile deformation, the stiffness and ultimate shear deformation capacity are maintained after the tensile deformation, also, the compressive, shear stiffness, and shear deformation capacity are maintained after the tensile deformation (Takayama et al., 2004).

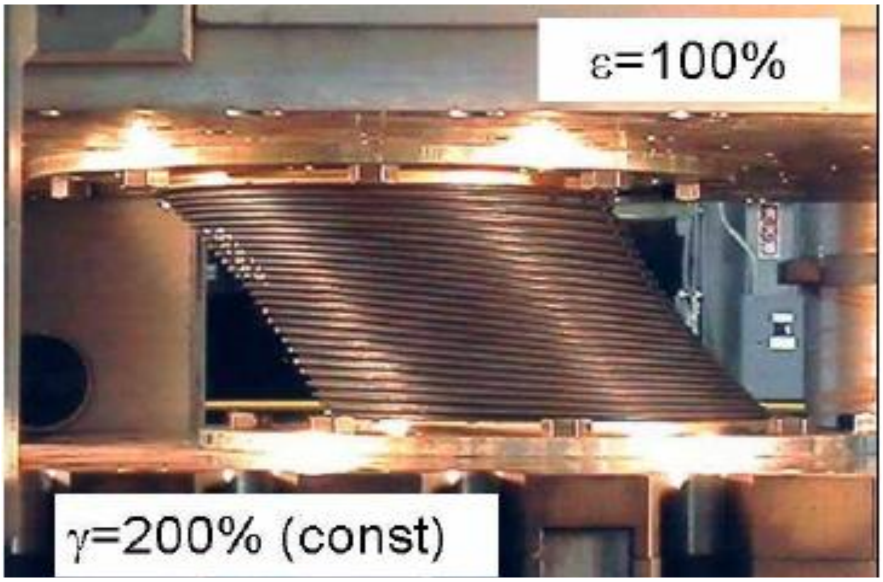


Figure 2.4 Natural rubber bearing under tensile deformation (Takayama et al., 2004)

2.2.2.3 Lead-plug bearings

The lead-plug bearing was invented in New Zealand in 1975 and has been used extensively in New Zealand, Japan, and the United States (Tyler and Robinson, 1984). Lead-plug bearings are laminated rubber bearings similar to low damping rubber bearings but contain one or more lead plugs that are inserted into holes, as shown in Figure 2.5. The steel plates in the bearing force the lead plug to deform in shear. Using countersunk bolts to connected the bottom and top plates to the rubber bearing. Cut the plug longer by an amount less than 5% than the height of the rubber bearing. The lead core expands in horizontal direction and wedges into the layers of rubber between the plates of shim. By this way, the energy dissipation capacity was provided by the lead core. The mechanical property of lead strength that depends on some parameters such as, the amplitude of motion, the axial load on the bearing, the lead core size, and the manufacturing details of bearing. furthermore, the effective yield stress has different values from cycle to cycle according to the result of lead core heating. The stress around 10 MPa is deforms the lead of bearing, providing the isolation system with a bilinear response. In the elastomeric bearing a lead must fit tightly in the system, and this is achieved by making the lead plug slightly larger than the hole and forcing it in. Generally, the displacement of bearing dependent on the effective damping and effective stiffness of the lead-plug, so must be state the displacement at which a specific damping value is required (Hu, 2014).

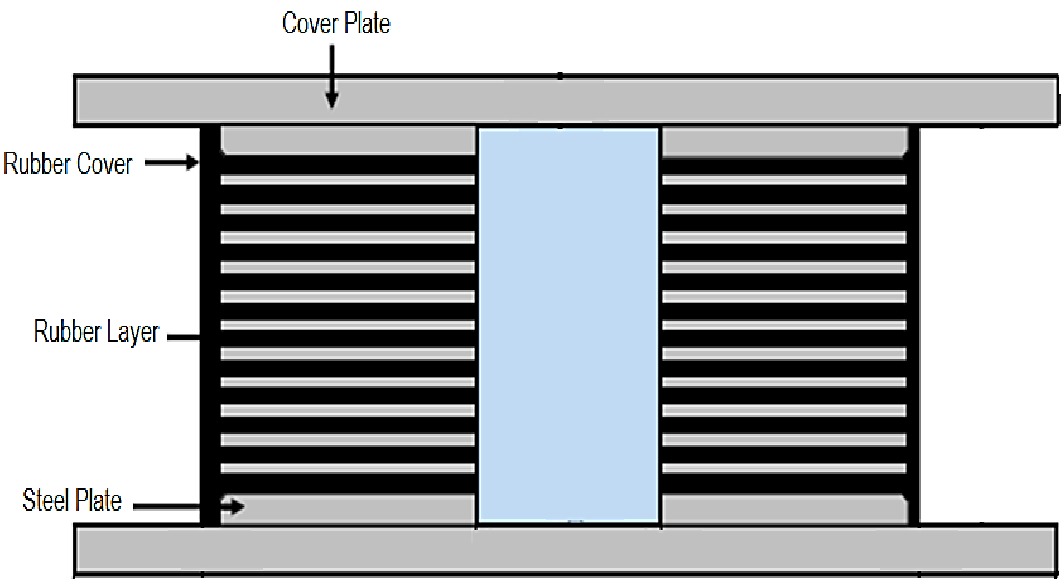


Figure 2.5 Schematic view of an LRB isolator device (Hu, 2014)

2.2.2 Isolation systems based on sliding

The earliest and simplest isolation system was proposed is a sliding system by Calantarients, in 1909, which used the layer of talc as shown in Figure 2.6 to separating the structure from the foundation. He has found that the system of isolation decreased the accelerations in the isolated building as well as the relative displacements between the superstructure and the foundation, for he designed a set of ingenious connections for utilities in those circumstances to gas lines and sewage pipes to control on these displacements (Naeim and Kelly, 1999).

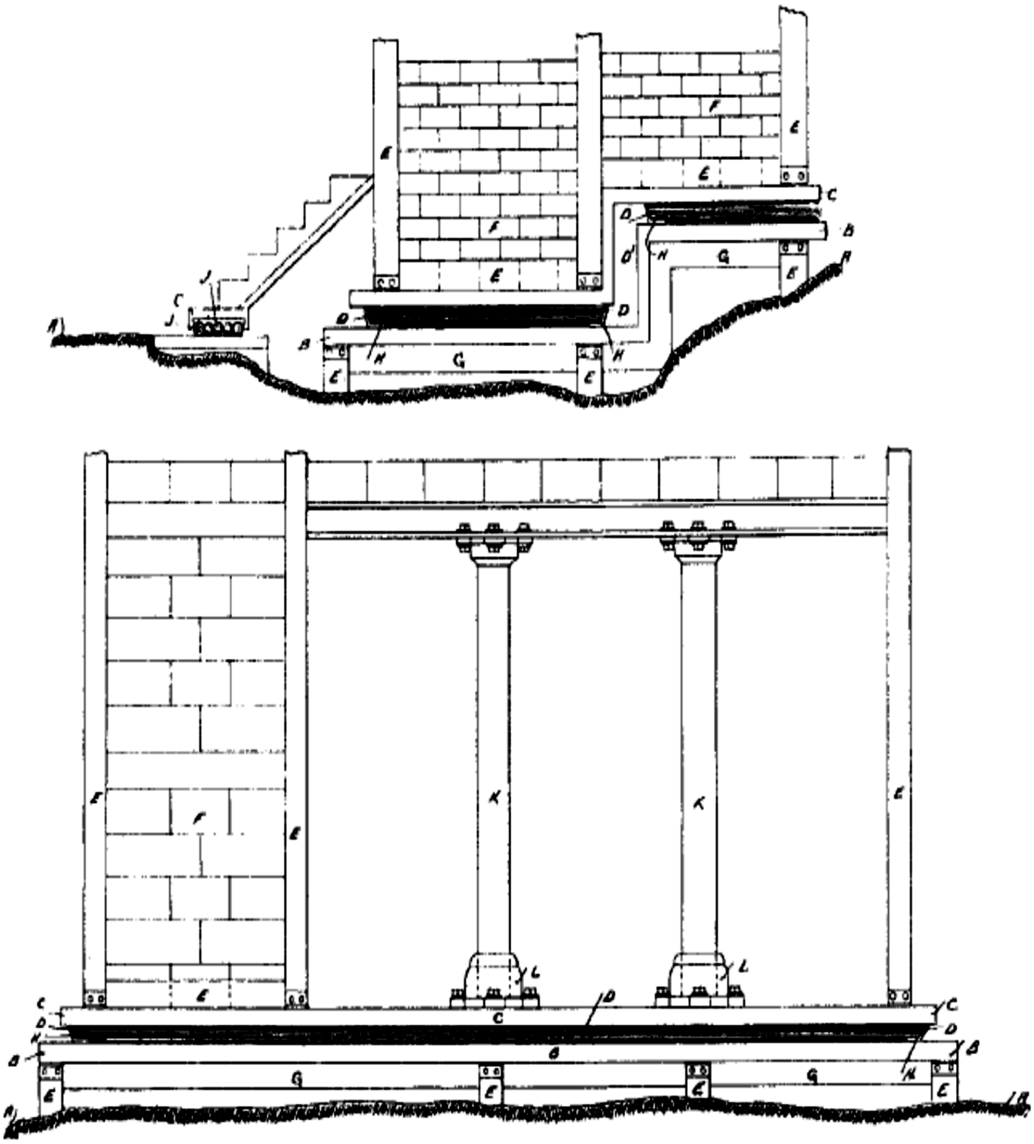


Figure 2.6 Calantarients's base isolation system (Naeim and Kelly, 1999)

2.2.2.1 Resilient-friction base isolation system

Several attempts were made to conquer the problem of the high friction coefficient of Teflon on stainless steel at altitude velocities by employing many sliding interfaces in a single bearing, one of these attempts is the resilient-fraction base isolation (R-FBI). Where the velocity between the upper and lower level of the bearing is divided by the number of layers so that the velocity at each face is decrease, maintaining a low friction coefficient. In addition to this, there is a central core of rubber that provides a restoring force without carrying any vertical loads. Tests of this system found that the rubber core did not prevent the displacement from being concentrated at a single interface; therefore, a central steel rod was inserted in the rubber core that improved the distribution of displacement among the sliding layers (Mostaghel, 1984).

2.2.2.2 Friction pendulum system

One of the most important types of isolation and widespread use is the friction pendulum system (FPS). Friction pendulum bearings have several of configurations: single, double or triple as illustrated in Figure 2.7 a sections of single and double FPS bearings. Also the design of a double FPS may be with the two sliding interfaces, that having various frictional and geometric properties. Furthermore, the Single FP system in the same figure is shown with the pivot point located outside the boundary of the concave sliding surface. Also the pivot point is possible located inside the boundary of the concave surface (Fenz and Constantinou, 2006).

The working principle of a friction pendulum system depends on the combination of a restoring force and a sliding action. It has an articulated slider that moves on the spherical surface of stainless steel, the side of the articulated slider in contact with the spherical surface is coated by the composite material of low-friction. The damping in this isolator is produced by friction between the spherical surface and the articulated slider. The radius of curvature of the concave surface is the one that controls in time period and the effective stiffness the buildings (Al-Hussaini et al., 1994).

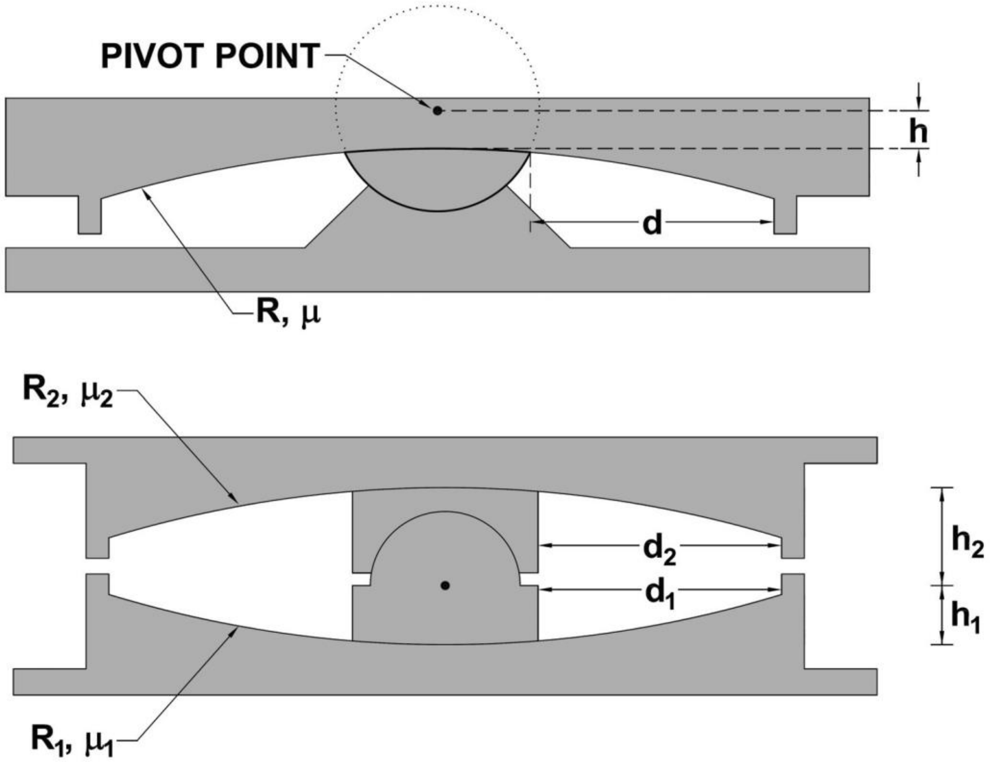


Figure 2.7 Cross sections of single and double friction pendulum bearings (Constantinou et al., 2011)

2.2.2.3 Spring type systems

Most isolation systems provide one-dimensional isolated, usually is horizontal direction. There is sometimes a need to use three-dimensional isolators, but not common, this type of systems is using in these cases. It is manufactured by using a large helical steel springs that are flexible in both directions (horizontal and vertical) as shown in Figure 2.8. In three-dimensional systems, since the center of gravity of the isolated building is above the center of stiffness of this device so the coupling between horizontal motion and rocking motion is very strong. This type is used in installations where the center of gravity and the center of hardness at the same level, for example in a reactor vessel in a nuclear power plant. It has been implemented od this system in steel frame building, response of the building was observing during a strong motion. It noted that the isolator device was not effective in decrease the accelerations in these buildings due to the rocking motion (Makris and Deoskar, 1996).

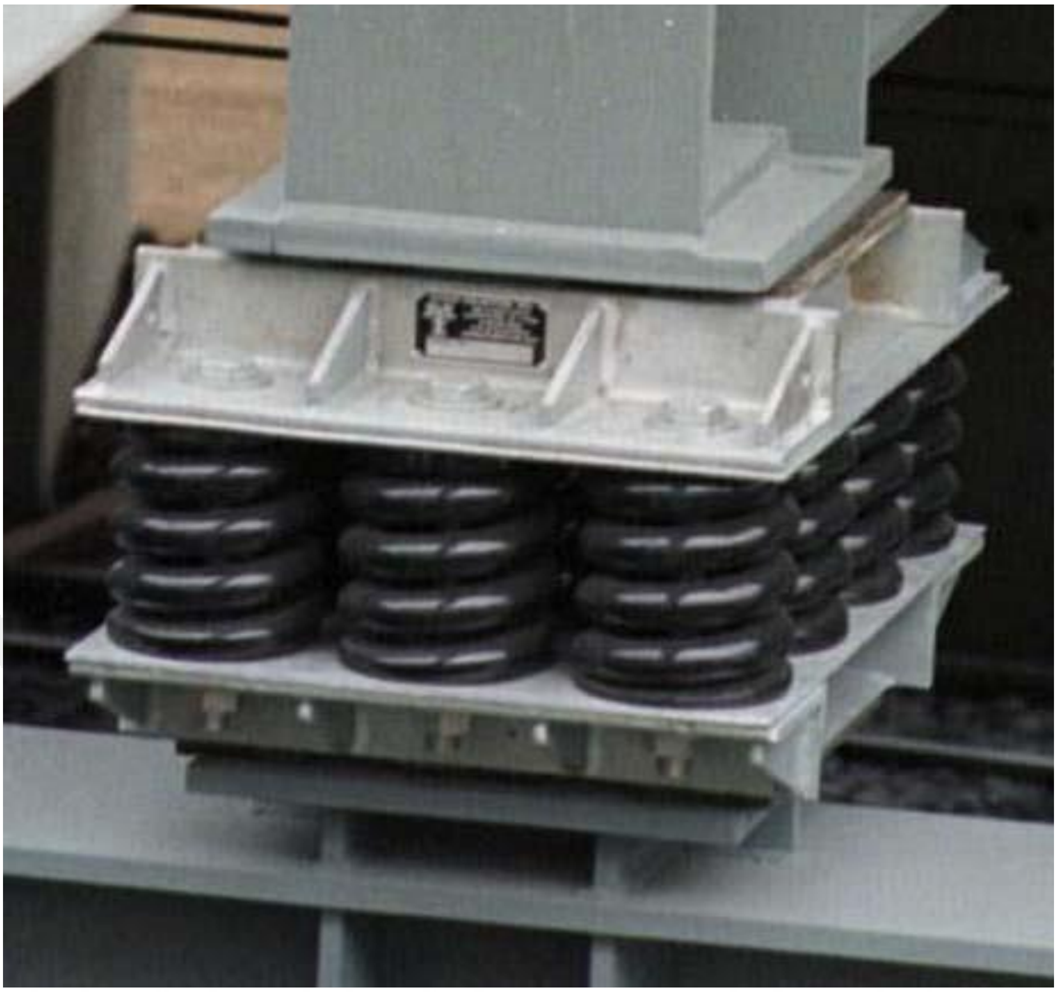


Figure 2.8 Spring type systems (www.mason-ind.com)

2.3 Development of seismic isolation worldwide

The concept of isolated building has become a practical reality within the last 20 years with the evolution of multi-layer elastomeric isolation, which are manufactured from vulcanization bonding of sheets of rubber with thin steel reinforcing plates. These isolator devices are very rigid in the vertical direction, and it can be carrying a vertical load of the structure, but it is very flexible in the horizontal direction, that way it was allowing to the structure movement horizontally under the influence of lateral motion. The development of base isolation was an extension of the employ of elastomeric device to isolated the important structures. In recent years' the other types of systems have been developed by modifications of the sliding system. Where earthquake-prone areas are increasing widespread demand using basal isolation in various structures. In 1969 the first use of a rubber isolation system in an elementary school in Skopje, Yugoslavia to protected from earthquakes. The Pestalozzi School was shown in Figure

2.9 has a three-story concrete built by Swiss engineers, the isolation system of this building is known as the Swiss Full Base Isolation-3D (FBI-3D) System. In this isolation bearing used the rubber blocks as Figure 2.10 are completely unreinforced so that it suffers bulge sideways due to the weight of the structure. Also, it has been put a Glass blocks as Figure 2.11 to acting as seismic fuzes are intended to break if the seismic loading exceeds a certain threshold. Due to the vertical and horizontal stiffness of the device is about the same, the building will movement to backward and forward in an earthquake. These isolators were designed in period a technology was poorly for reinforcing rubber with steel plates, and it is unlikely that this system will be used again (Kelly, 1981).

Figure 2.9 Pestalozzi school, skopje. Macedonia (Kelly, 1981)

Figure 2.10 Bearings used in the Pestalozzi school (Kelly, 1981)

Figure 2.11 Seismic fuzes used in the Pestalozzi school (Kelly, 1981)

Base isolation is a strategy for reduction the effects of the seismic force on the structurs by the use of a number of possible mechanisms which uncouple the construction from the horizontal components of the earthquake ground motion and support the vertical weight of the construction. While many base isolation systems have been proposed over the years, until recently none has been considered sufficiently practical to be implemented. With the development of multilayer elastomeric isolator, the concept has become a practical possibility. The bearings for use in a seismic isolation system for buildings are a development of elastomeric bridge bearings. The vertical stiffness of the bearings is high and the horizontal stiffness low. Many years of experience with bridge bearings have shown that they are equivalently as strong and reliable as reinforced concrete components in bridges. Recognition of the engineering qualities of elastomeric bearings has led to their application in a seismic base isolated in several countries. The concept of base isolation has also provided a rich source of theoretical work, both in the dynamics of the isolated structural system and in the mechanics of the isolators. This theoretical work, widely published in structural engineering and earthquake engineering journals, has led to design guidelines for isolated structures and design rules for isolators. Many countries are now formulating design codes for isolated structures. In the United States design codes have been in employing since 1986. The code writing process has undergone a steady evolution through a code series that began with a simple regulation titled “Tentative Seismic Isolation Design Requirements” based at most on equivalent static design methods, which was considerably modified and became the 1991 version of the Uniform Building Code (UBC), “Earthquake Regulations for Seismic Isolated Structures” (Kelly, 1983).

At the beginning of the eighties of the last century was the use of base isolation to reduce the response of structures to seismic activity was not regarded as a realistic approach and was met with great skepticism by the engineering community. After a slow start, the concept is gaining widespread acceptance. The extent of this acceptance can be gauged by the large number of journal articles, technical reports, workshops, and symposia devoted to the topic. The first base-isolated building to be built in the United States was the Foothill Communities Law and Justice Center which appears in Figure 2.12, located in the Los Angeles city. Not only was it the first isolation system in United States, it was also the first building that using the isolation device in the world, which made from high-damping natural rubber (Tarics et al., 1984).

Figure 2.12 Foothill Communities Law and Justice Center (Taric et al., 1984)

The building, approximately 15,794 m^2 and a 4 stories rise with a full basement, was designed to withstand an 8.3 magnitude earthquake. Located in a special sub-basement, a total of 98 bearings were used to isolate the building. The construction of the building began in 1984 and finished in mid-1985. Four high-damping natural rubber compounds were developed by the (MRPRA) which that mean Malaysian Rubber Producers' Research Association of the UK for this building. The isolator devices made from a highly filled natural rubber, as shown in Figure 2.13. The isolation system has high horizontal stiffness and a short period; as the load intensity increases, the stiffness drops and the period is lengthened. The damping follows a similar but less dramatic pattern, decreasing from an initial value of about 20 % to a minimum of around 10% and then increasing again. The system is designed so that the minimum values of damping and stiffness are assumed, and the response is taken to be linear (Tarics et al., 1984).

Figure 2.13 Typical of Natural rubber isolator (Tarics et al., 1984)

The San Francisco City Hall as shown in Figure 2.14 was designed in 1912 to replace the previous structure that was destroyed in the 1906 San Francisco earthquake. An outstanding example of classical architecture, which was suffered to damage from 1989 Loma earthquake necessitated extensive repair. The repairing strategy adopted for the building was a base isolation scheme with superstructure strengthening using concrete shear walls. The structural system is a steel frame with unreinforced brick masonry. The flexible first story approach to seismic design was first proposed in the 1930s and again as the soft first story in the 1960s to a certain extent it is a precursor of the base isolation approach. The primary goal of the repairing strategy was to preserve the historic fabric of the building. Many options were considered and base isolation was selected. The plane of isolation is just above the existing foundation. Construction began in 1994, where the building shown in Figure 2.15 have isolated by 530 lead-plug rubber isolator devices. Many of the columns are supported on four isolators under a cruciform steel structure (Naaseh, 1995).

Figure 2.14 San Francisco City Hall (Naaseh, 1995)

Figure 2.15 Base isolation device (Naaseh, 1995)

The Los Angeles City Hall is a 28-story steel frame building completed in 1928, with a total floor area close to 83,000 m^2, as appears in Figure 2.16. The building was Suffered damage in the 1994 due to Northridge earthquake, with the most severe damage occurring on the twenty-fifth and twenty-sixth floors, which are characteristically soft stories. The base isolation retrofit scheme used about 475 high damping rubber device in combination with about 60 sliders and was supplemented by about 52 mechanical viscous dampers at the isolation level. Moreover, 12 viscous dampers installed between the twenty-fourth and twenty-sixth floors to control inter-story drifts at the soft-story levels (Youssef et al., 1995).

Figure 2.16 Los Angeles City Hall (www. wikipedia.org)

In Japan, the base isolation concept has been studied for quite a long time. Since Kozo Kawai's paper appeared in 1891, a wide variety of base isolation concepts have been reported. However, research and development activities on base isolation technologies started in the late 1970s since laminated rubber bearings were introduced from Europe. Since the early 1980s, practical applications have become common, which accelerated research and development efforts. This was made possible by the maturity of basic technologies in response to demand from the construction market, and a result of the comprehensive development of relevant technologies. Leading construction companies played a major role in this development process, combining extensive development activities with experimental studies on isolation devices, the development of analytical methods, evaluation of earthquake ground motions, investigation of maintenance procedures, and the trial construction at their own facilities. The major isolation devices which have led to the practical implementation are the laminated rubber bearings using natural rubber, which are commonly used with some kinds of dampers, the lead rubber bearings, sliding bearings, and high damping rubber bearings. The use of isolation for seismic-resistant design is activated in Japan, with the completion of the first large modern base-isolated building in 1986 and increased to a level of around 10 isolated buildings per year in 1990 and 1991. The rate of construction of isolated buildings had dropped to around 4 or 5 per year due to the economic turndown, and at the time of the January 1995 Kobe earthquake the number stood at around 80. The isolation systems most commonly used in the past were natural rubber bearings with mechanical dampers or lead-plug rubber bearings, and high-damping natural rubber isolators. The largest base-isolated building in japan is the Postal Computer Center (Figure 2.17). It has area up to 47,000 m^2, building is supported on 120 elastomeric isolators, with a number of additional steel and lead dampers. The building was exposed to Kobe earthquake in 1995, peak ground acceleration under the isolators was 400 cm /s^2 (0.41 g) and was reduced by the isolation system to 127 cm /s^2 (0.31 g). The displacement of the isolators is up to 12 cm, there was no damage to the building after the end of the earthquake. Generally, the total number of isolated buildings reviewed by the special Ministry of Construction committee in Japan as of March 1997 stands at 393 included hospitals and local government buildings (Blake, 1995b).

Figure 2.17 The Postal Computer Center (www.wikipedia.org)

In Europe, base isolation has been studied and developed most actively in Italy under the auspices of the National Working Group on Seismic Isolation (Gruppo de Lavoro Isolamento Sismico (GLIS)). GLIS has a wide membership comprising researchers and practitioners, it has organized several workshops and is preparing design guidelines for isolation systems. The development of isolated buildings was started in Italy in 1988. In addition to several bridges, applications of seismic isolation mainly concern both some important public buildings, which are critical for civil defense, and some first industrial structures. Base isolation has been or is being adopted in Italy in: (Martelli and Bettinali, 1992)

1. The Fire Command and Control Center Facility at Napoli (a suspended steel structure supported through neoprene bearings at the top of large reinforced concrete columns), which was the first pioneering application of seismic isolation in Italy.
2. Five large buildings (seven floors, 25 m height, 70,000 to 78,000 kN weight each), designed by Giuliani (G.C. Giuliani, 1989), which were completed at Ancona (Figure 2.18), (those forming the new Administration Center of the National Telephone Company SIP - for the Marche Province).

After that several buildings have been built in Italy using base isolation such as: standardized precast telephone switch houses, building for Ministry of Defense at Ancona, and the four-story Operating Center of the Traffic Police at Napoli (Giuliani, 1991).

Figure 2.18 The SIP Complex, Italy (Giuliani, 1991)

While that, the first base-isolated building in New Zealand was the William Clayton building in Wellington. Completed in 1981, it was the first building in the world to be isolated on lead-rubber bearings (Charleson et al. 1987). After its completion, three other base-isolated buildings have been built in New Zealand; two of these structures (Union House Auckland, and Wellington Central Police Station) are isolated using the sleeved-pile approach. The Union House (Figure. 2.19) is a 12-story reinforced concrete braced frame. Displacement control is provided by an additional damping system based on the elastic-plastic deformation of mild steel tapered plates. The Wellington Central Police Station is a 10-story reinforced concrete braced frame structure, and displacement control is effected by lead extrusion dampers (Boardman et al., 1983).

The National Museum of New Zealand in Wellington is isolated with 142 lead-rubber bearings and 36 Teflon pads under the shear walls. Another notably isolated building is the New Zealand Parliament House. It was retrofitted using isolation, the Parliament House is a masonry bearing wall structure originally completed in 1922; this building and one other building were isolated using more than 514 lead-rubber bearings (Poole and Clendon, 1991).

An unusual isolation project is a printing press building located in Petone near Wellington. This building was built on lead-rubber isolators, where the purpose of the isolation system is to protect the printing presses, which are very large and brittle pieces of equipment. The presses are made of cast iron and are equivalent in height to a four-story building. The building structure surrounds and is connected to the press, and the entire system is isolated at the base *(*Dowrick et al., 1991).

Figure 2.19 Union House, New Zealand (Boardman et al., 1983)

It is now generally accepted that a base-isolated building will perform better than a conventional building in moderate and strong earthquakes. A number of buildings so designed have experienced such earthquakes and their response has confirmed these expectations. The major benefit of isolation in such cases is to reduce damage to contents and sensitive internal equipment and in many buildings, such as computer manufacturing facilities, emergency preparedness centers, and hospitals, the reduction of damage to equipment is of sufficient importance to justify the increased initial cost of isolated construction (Kelly, 2011).

CHAPTER 3

CASE STUDY

3.1 Description of analytical modelling

In this study, the lead rubber isolators were designed and shown their influences on the seismic response of the mid and high rise steel framed structures, and compared with the fixed base cases. Figures 3.1 to 3.4 show the plan and elevation views of the case study structures. For this purpose, analytical models of the buildings were constructed and their responses were investigated by using the time history analysis under three ground accelerations. The assumptions below were considering:

- Three buildings having 5, 10 and 15 stories were investigated. These buildings have the same plan with 6 bays having 6 m length in x direction and from 3 bays having 6, 4, and 6 m length in y direction. The story height of the buildings is 3.6 m from floor to floor, and slab thickness concrete is 180 mm.
- A grade of steel as S355.
- Size of columns are HEB300 (high 300 mm, width 300mm, t_w 11mm, t_f 19mm) and beams are IP300 (h 300 mm, b 150 mm, t_w 7.1mm, t_f 10.7mm).
- For the gravity loading uniformly distributed on the slabs, where its include; dead load of 5.5 kN/m^2, live load and roof live load of 5, 1.5 kN/m^2, respectively (considering participation factor of 0.6), snow load = 1.25 kN/m^2 (with a participation factor of 0.3), and finishing load of 1 kN/m^2.
- The seismic force applied as a nonlinear dynamic load of time history with earthquake function on X-direction with damping ratio 5%. And the site located in seismic zone 3 therefore the effective ground acceleration coefficient (A_o)=0.2
- The residential buildings constructed on a soil of group c in the region of the local site class Z3.

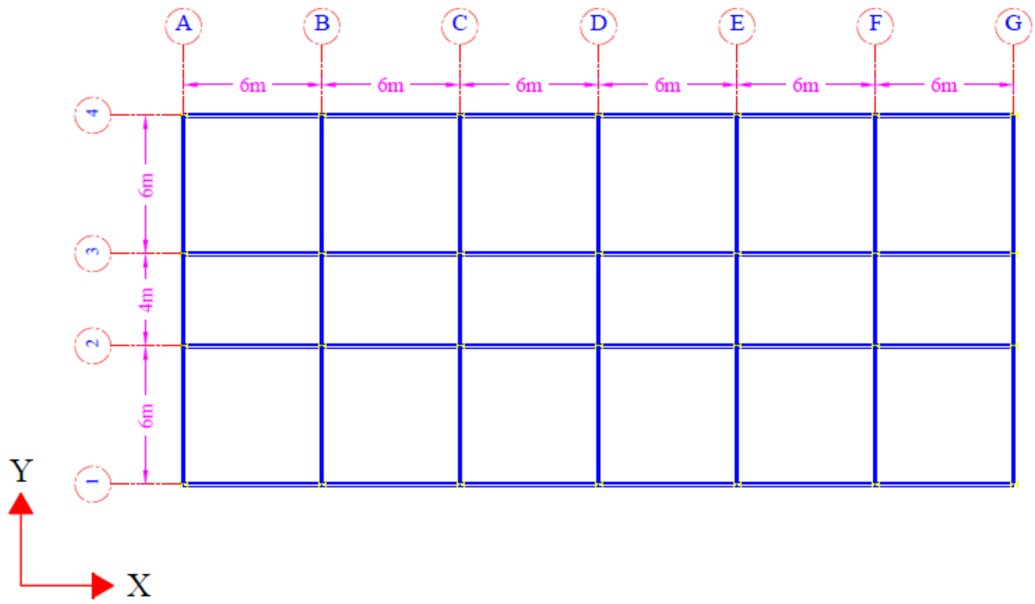


Figure 3.1 Typical plan view of steel frame building

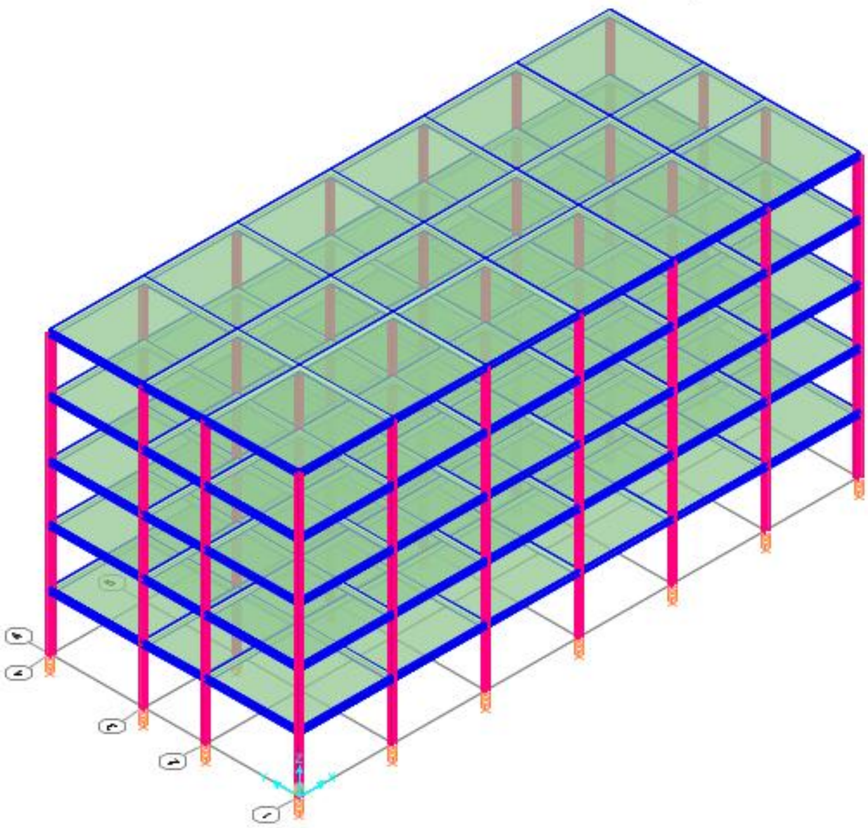
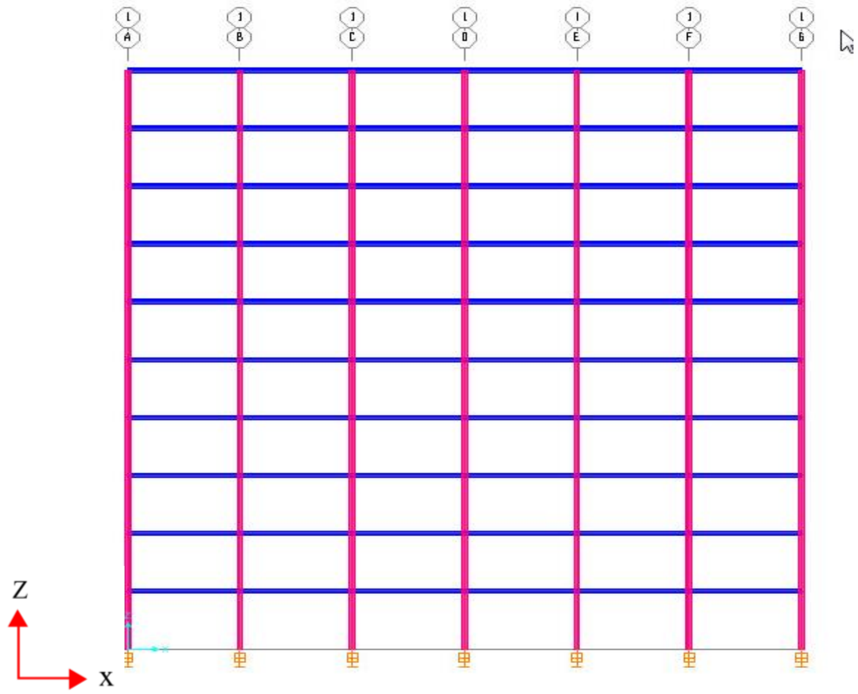
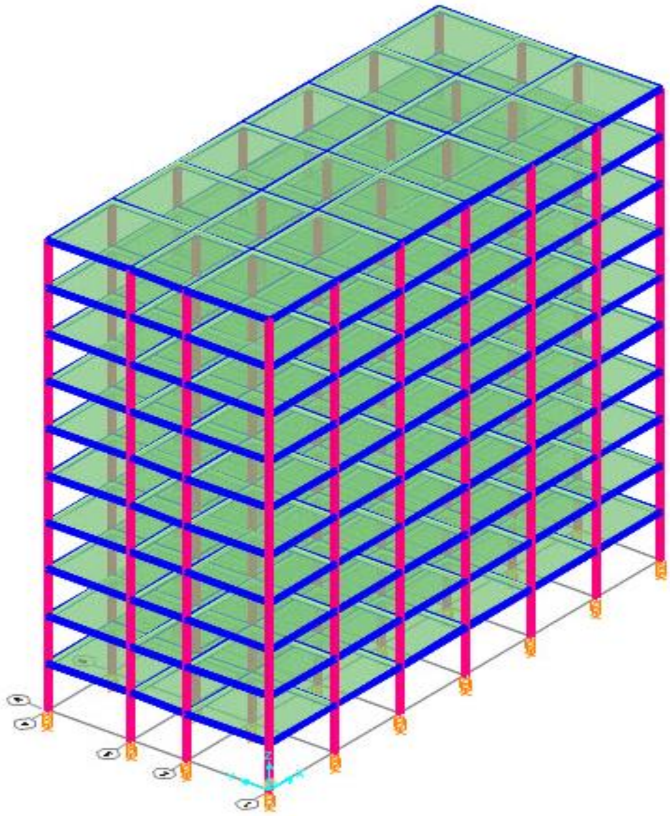


Figure 3.2 Three dimensional views of 5-storey building

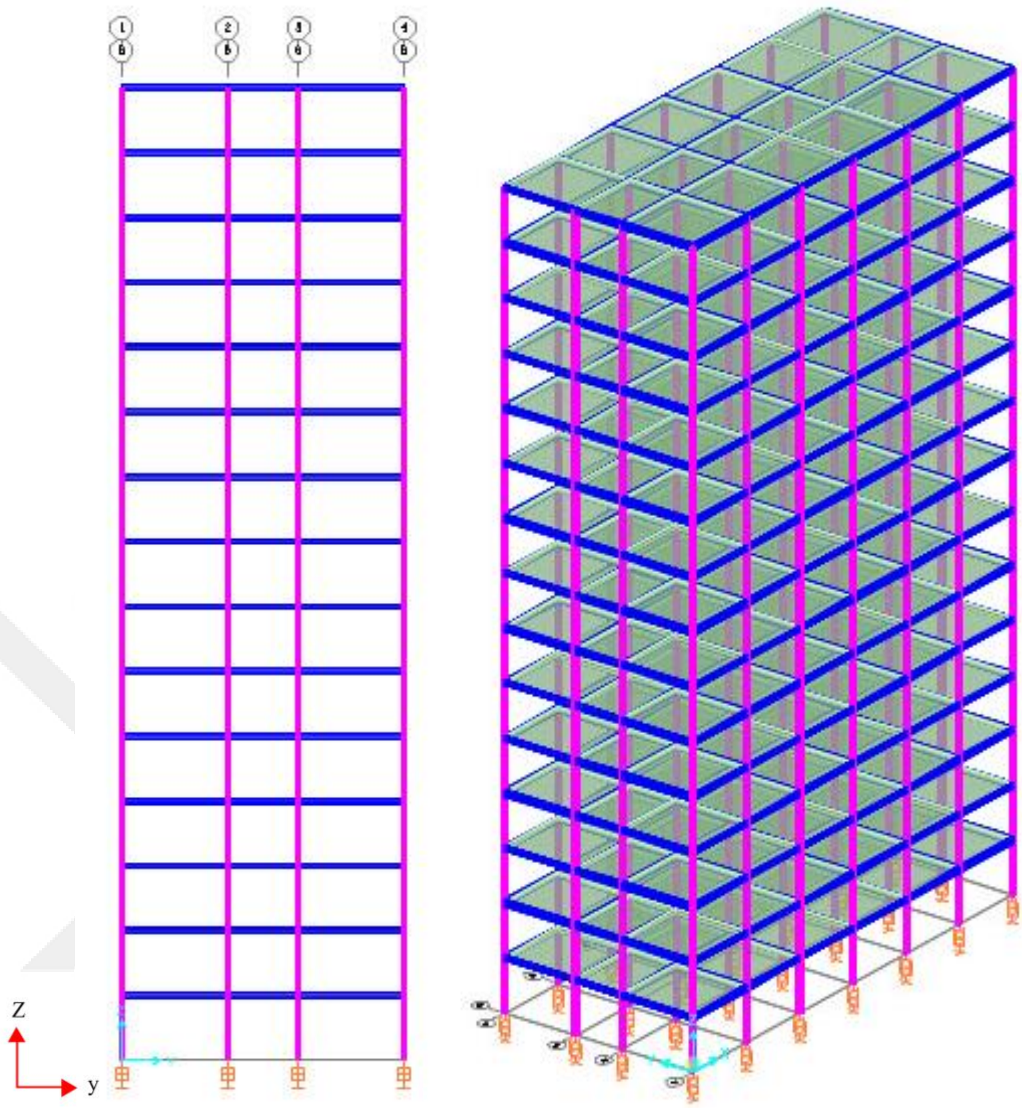


a)



b)

Figure 3.3 Front and three-dimensional views of 10-storey building



a) b)

Figure 3.4 Side and three-dimensional views of 15-storey building

3.2 Lead-rubber isolators and nonlinear analysis

Lead-rubber isolators are one of the types elastomeric bearings fitted with a central lead core to increase the dissipation of energy in the time of the displacement was occurring due to the earthquake. These isolators are usually installed under the superstructure and sitting above the substructure. A section of a typical circular lead core rubber bearing is delineated in Figure 3.5. The isolation system consists of layers of vulcanized rubber trapped between layers of steel in the form of shims. In the middle of the isolation device has been inserted a solid lead-core. Steel plates were installed to the top and bottom of the isolators in order to link the sub- and superstructures. The rubber layers are responsible for providing flexibility in the horizontal direction. While the steel plates provide sequestration to the lead core, affordability of vertical loads, and vertical stiffness of the device. In addition, the rubber cover provides protection for the steel layers from environmental influences. Generally, the isolator is very stiff and strong in the vertical direction, but flexible in the horizontal direction (Buckle et al., 2006).

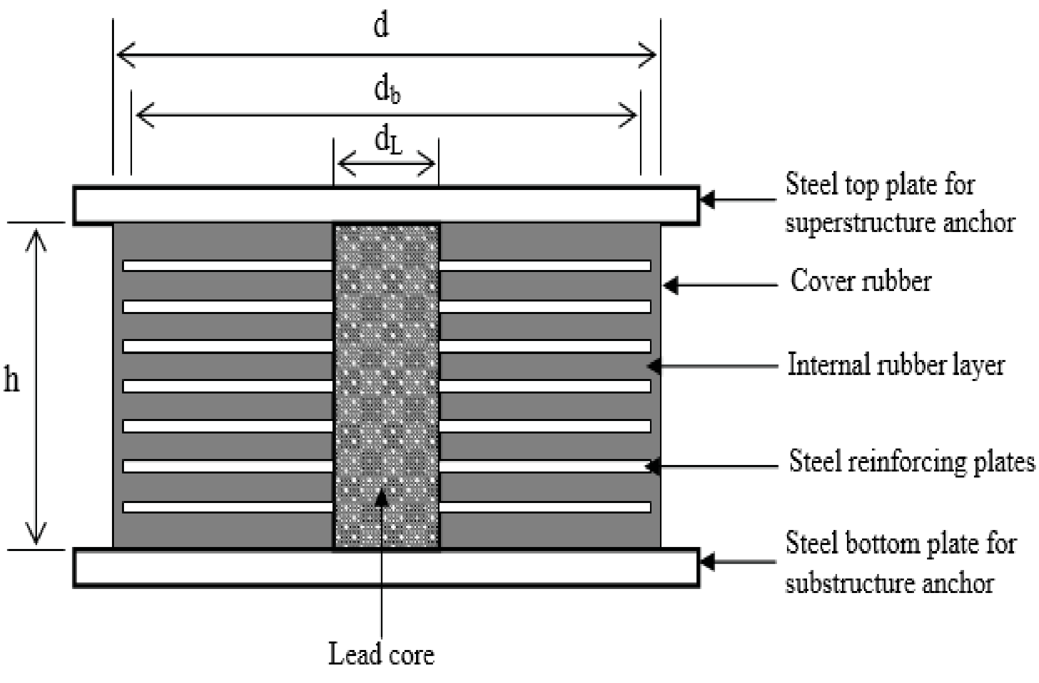


Figure 3.5 Sectional view of lead core rubber isolator (Buckle et al., 2006)

It should be noted that the square or rectangular cross-section of the isolation system has the same behavior. Where the movement of the structure is controlled by both the lateral stiffness of the rubber layers and the lead core. When ground motion occurs due to earthquakes, the steel layers in isolator device force the lead-core to deform in shear. The rubber layers then easily deform in shear providing the lateral flexibility to elongate the period of the structure. The deformation of the isolation system under effected by the earthquake illustrates in Figure 3.6.

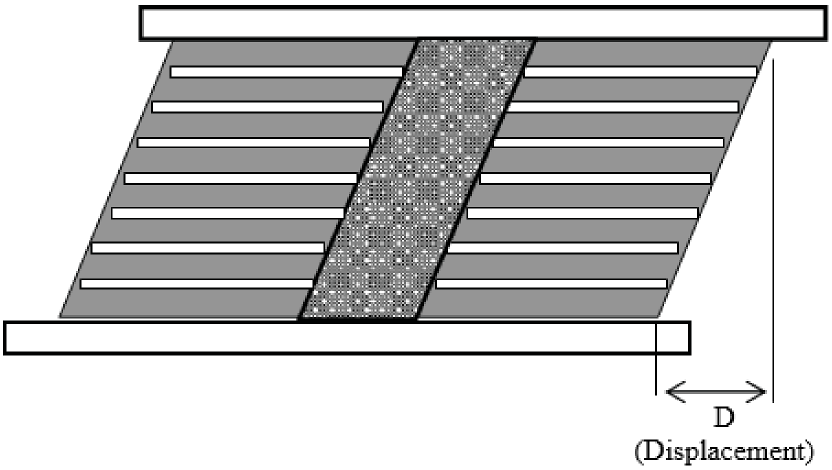


Figure 3.6 Shear deformation in a lead-rubber isolator (Buckle et al., 2006)

The isolation systems, which can be elastomeric systems, exhibit highly nonlinear behavior. The design principle of the base isolated structures is based on the restriction of the nonlinear behavior at the base and conservation of the elastic behavior of the upper structure. All of the isolation bearings in this study were modeled by a bilinear model, considering three parameters: pre-elastic stiffness (K_u), post-elastic stiffness (K_d), and characteristic strength (Q_d). As an example, the hysteretic model for the base isolation system is given in Figure 3.7 (Buckle et al., 2006). In the hysteresis loop of a bilinear isolator the characteristic strength (Q_d) and effective stiffness (K_{eff}) are determined as given in the following equations (AASHTO 1999 and ASCE 7-05, 2005):

$$T_{eff} = 2\pi\sqrt{\frac{W/g}{K_{eff}}} \tag{3.1}$$

$$K_{eff} = K_d + \frac{Q_d}{D} \tag{3.2}$$

$$Q_d = \frac{\pi}{2}\beta_{eff}K_{eff}D \quad (3.3)$$

$$\beta_{eff} = \frac{1}{2\pi}\left[\frac{E}{K_{eff}D^2}\right] \quad (3.4)$$

where E is the energy dissipated per cycle at the displacement D.

For the behavior depicted in Figure 3.5, the energy dissipated per cycle is given by:

$$E = 4Q_d(D - Y) \quad (3.5)$$

where Y is the yield displacement of the system.

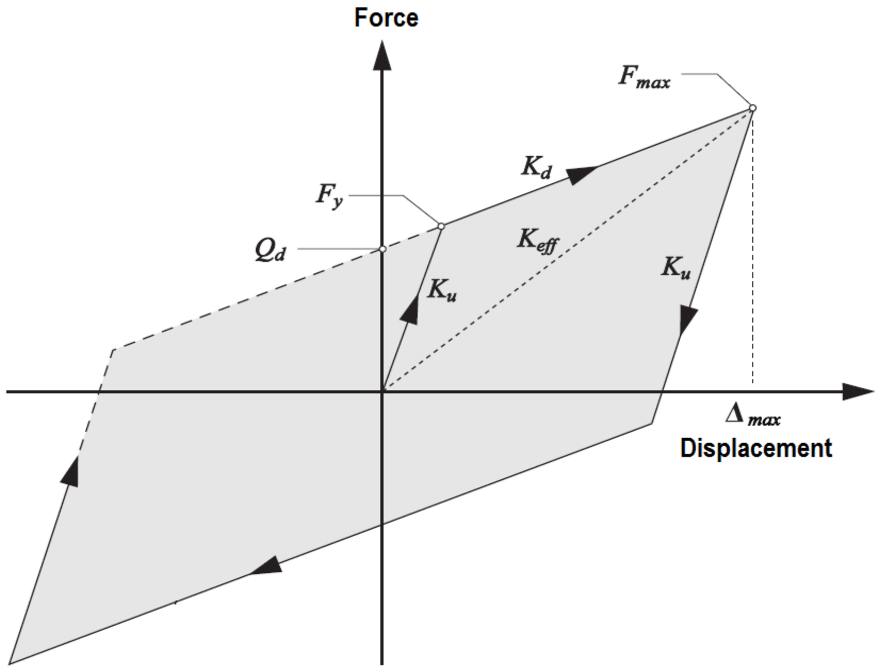


Figure 3.7 Hysteretic behavior of the base isolation system (AASHTO, 1999)

In order to apply the equations above, it has been assumed the displacement D, of the single-degree-of-freedom system with time period T_{eff} and viscous damping ration β, is given by AASHTO (1999), the equation was based on a calculation of the displacement:

$$D = 250\, A\, S_i\, T_{eff} / B \text{ (mm)} \quad (3.6)$$

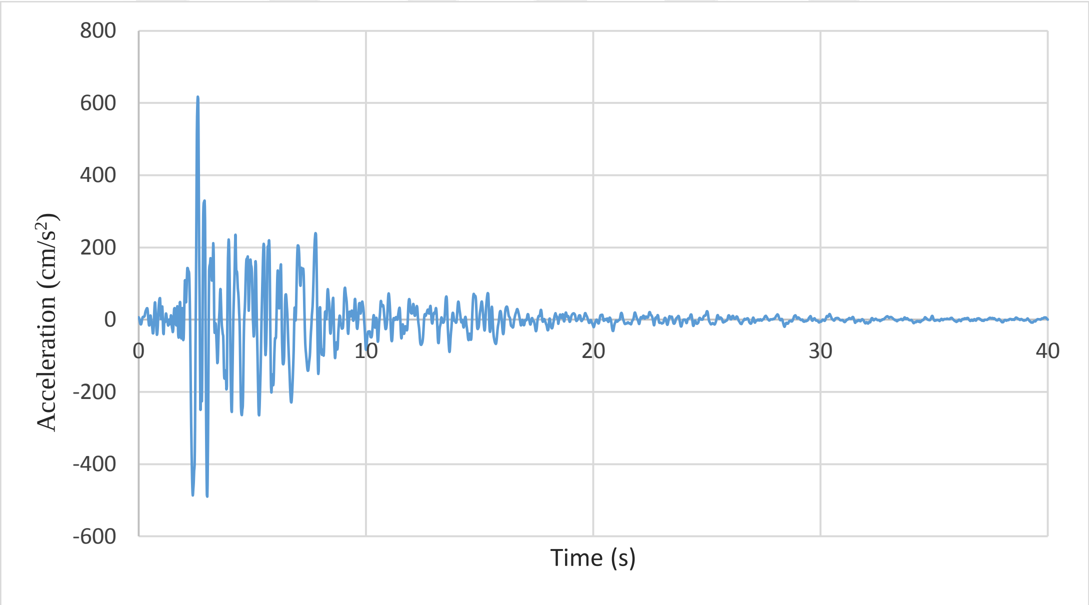
Where: A = acceleration coefficient for the site

S_i = site coefficient for isolated structures,

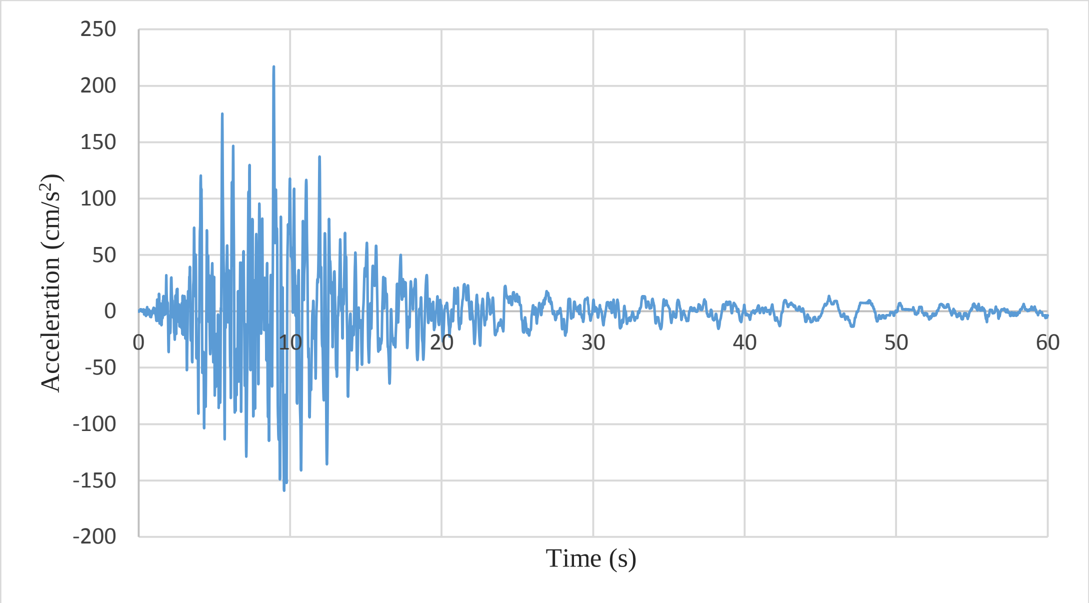
T_{eff} = effective period at displacement D

B = damping factor

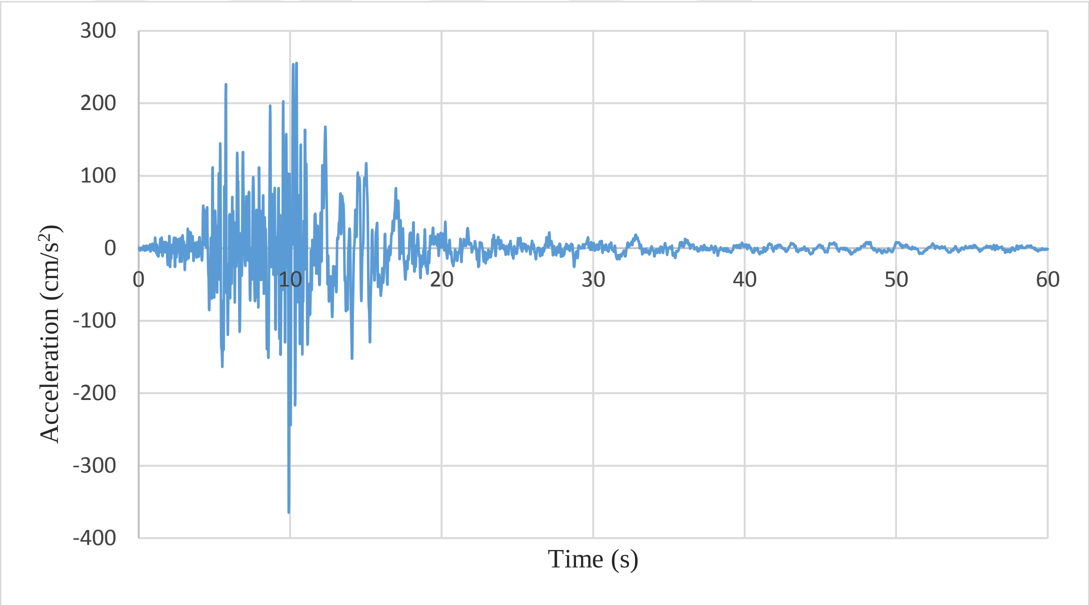
In this study and based on the assumptions previously mentioned for the site of the building, it has been considered the values of A= 0.2 for the site zone 3, S_i= 2 for soil type class 3, B= 1.2 for the damping ratio β= 10% (AASHTO, 1999), and T_{eff} has been assumed a three times of the time period. The analytical models of the base isolated and fixed based building models were obtained by using SAP2000 V.19 structural analysis program. For evaluation of the response of the buildings, comparatively, the nonlinear time history analysis was applied under three earthquake accelerations, namely: Corralitos (C), Northridge (N), and Santa Monica (SM). These earthquake accelerations motions are shown in Figure 3.8.



a) Corralitos (C)



b) Northridge (N)



c) Santa Monica (SM)

Figure 3.8 The earthquake accelerations used

CHAPTER 4

RESULTS AND DISCUSSION

In order to design the base isolation of the building, according to the number of floors, the parameters (the effective stiffness (K_e), characteristic strength (Q_d), post-elastic stiffness (K_d), and other parameters shown in Table 4.1) of lead rubber isolation, were obtained by using the equations mentioned in chapter 3. To achieve this, the nonlinear time history analysis has been done for each building with fixed base and base isolation devices under three different earthquakes of Corralitos (C), Northridge (N), and Santa Monica (SM). Table 4.2 shows the characteristics of the buildings.

Table 4.1 The parameters of rubber isolation

Building story	Effective stiffness K_{eff} (kN/m)	Effective damping	Yield strength Q_d (kN)	Initial stiffness K_d (kN/m)	Post to initial stiffness ratio
5 story	600.7	0.1	28.7	506.3	0.1
10 story	319.5	0.1	29.9	269.3	0.1
15 story	207.9	0.1	29.3	175.2	0.1

Table 4.2 Properties of the buildings

Building story	Time periods (s)	Load on bearing (kN)
5 story	1.215	1983.1
10 story	2.380	4047.9
15 story	3.593	6000.8

4.1 Analysis results of 5-story building

After installing the rubber base isolation and re-analysis of the building in order to compare the behavior of the base isolated building under different earthquake motions with fixed base building, the following results were obtained.

4.1.1 Corralitos (C) earthquake loaded on 5 story building

When this function was loaded, the maximum relative displacement has been reduced to 2.9 cm, while it had reached 12.3 cm with a fixed base building as shown in Figure 4.1. In addition to this, the variation of the inter-story drift demand with the story height were investigated as illustrated in Figure 4.2. As seen from the figure, the maximum inter-story drift demand decrease from 0.95% with fixed base building, to 0.4% for the base isolation system designed. Furthermore, the relative displacement with time between roof story and base were observed, and it was compared in Figure 4.3 for both cases of base isolated system and fixed base building. It's clearly seen from the figure, the using of base isolation decreased the relative displacement and reduced the response of building. Also, the variation of drift with time at all stories is given in Figure 4.4. Similar to the previous figures mentioned, with the base isolation, the drift significantly decreased in the structures in comparison to the fixed base case. It was also noted that the difference became more pronounced at the upper stories.

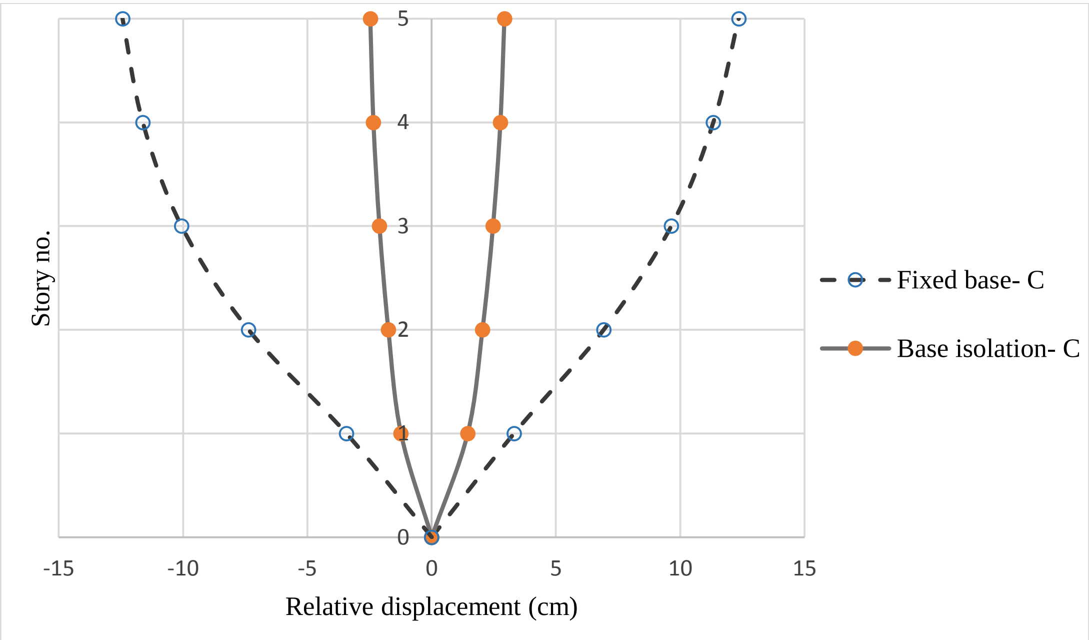


Figure 4.1 Relative displacement for 5 story model with fixed base and base isolation under Corralitos earthquake

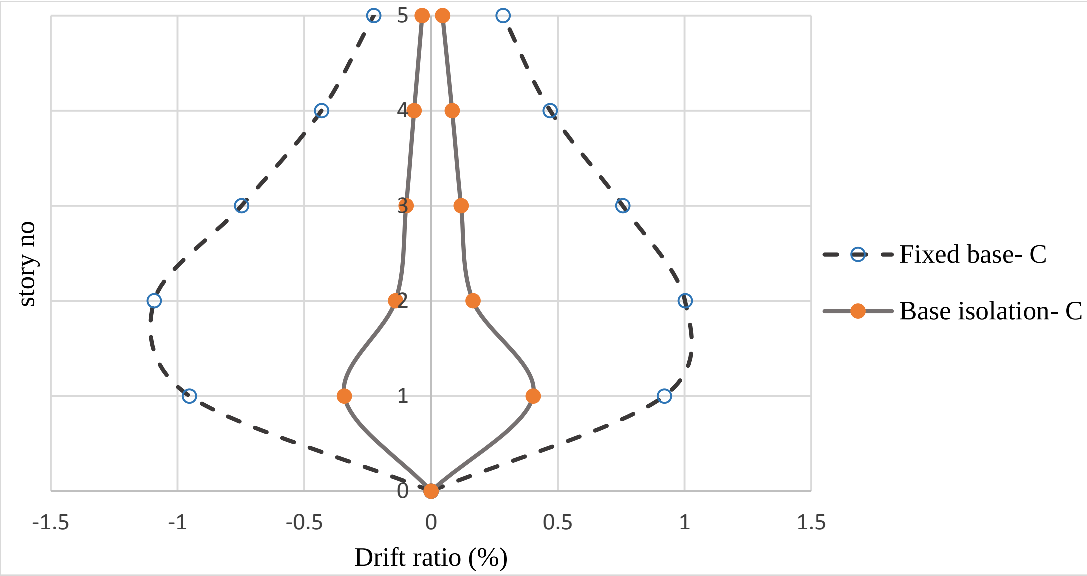


Figure 4.2 Drift ratio for 5 story model with fixed base and base isolation under Corralitos earthquake

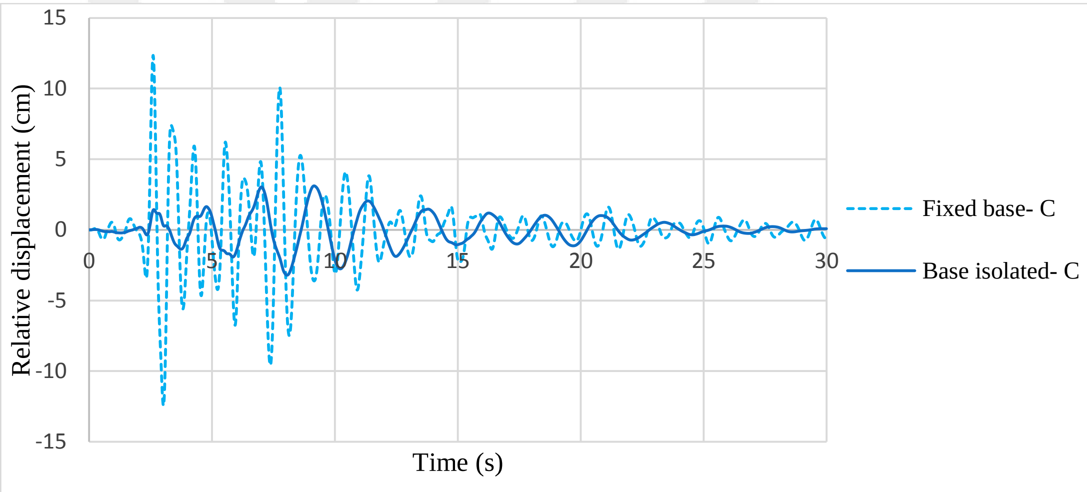
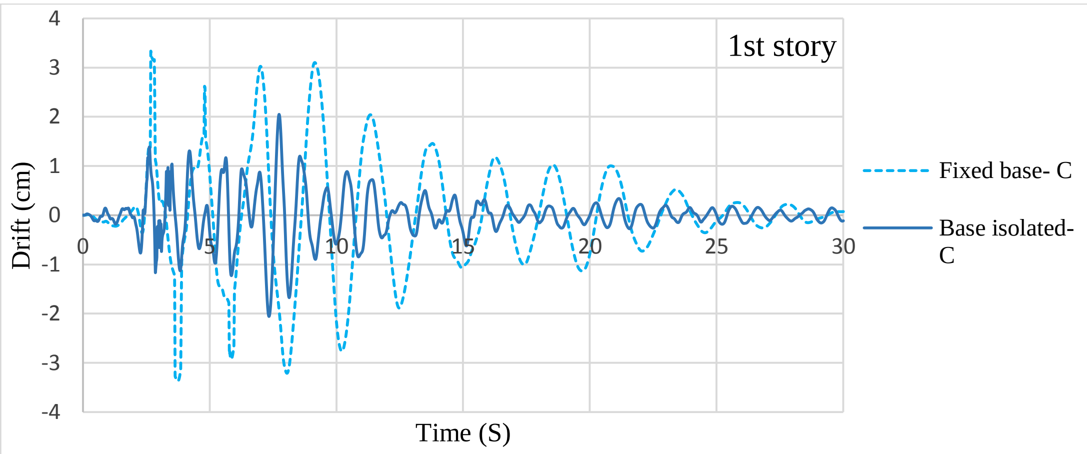
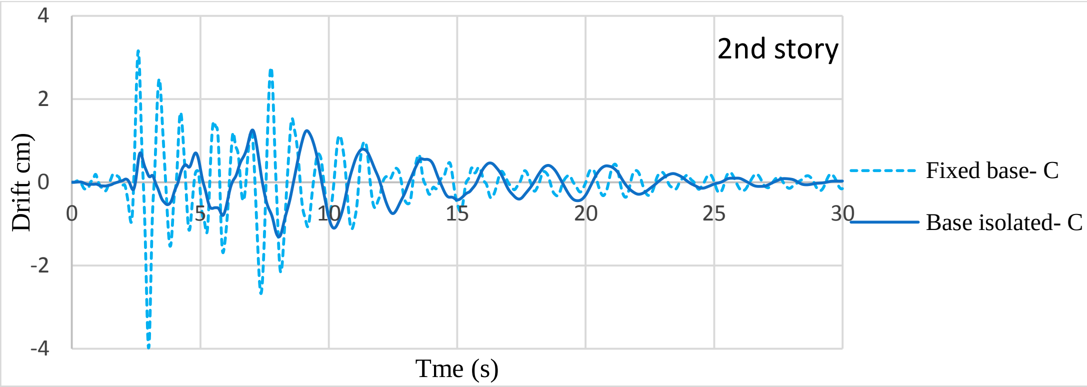


Figure 4.3 Relative roof displacement – time history plot of 5 story model under Corralitos earthquake



a)



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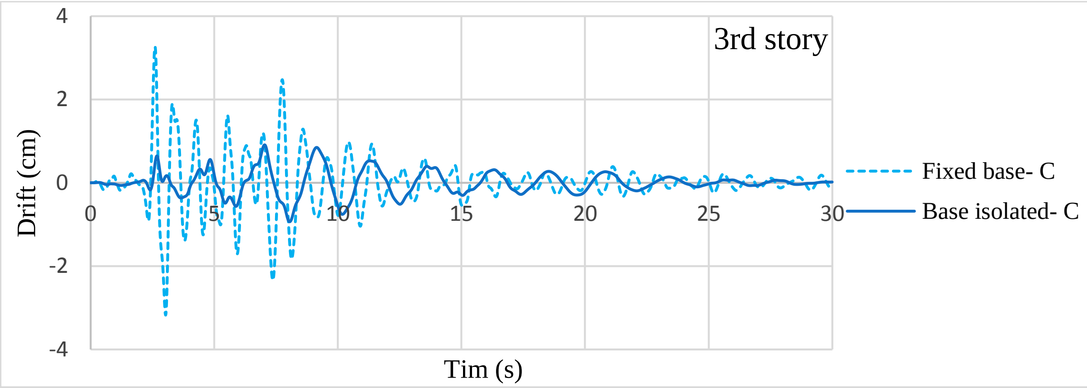

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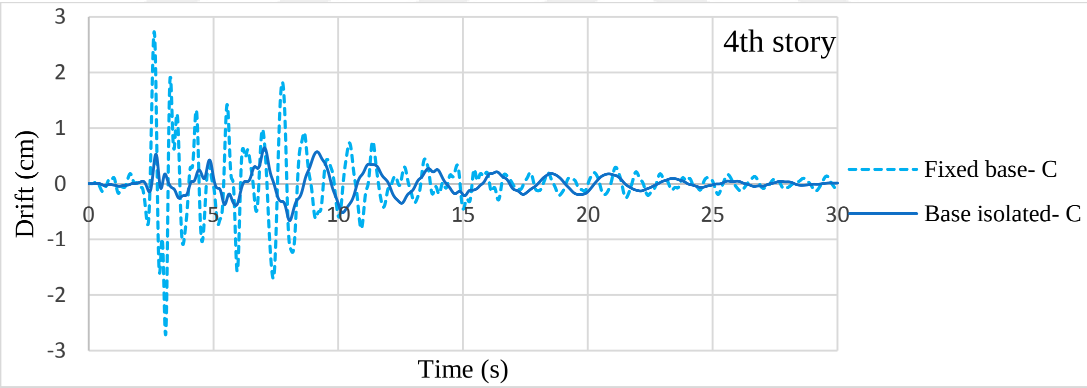

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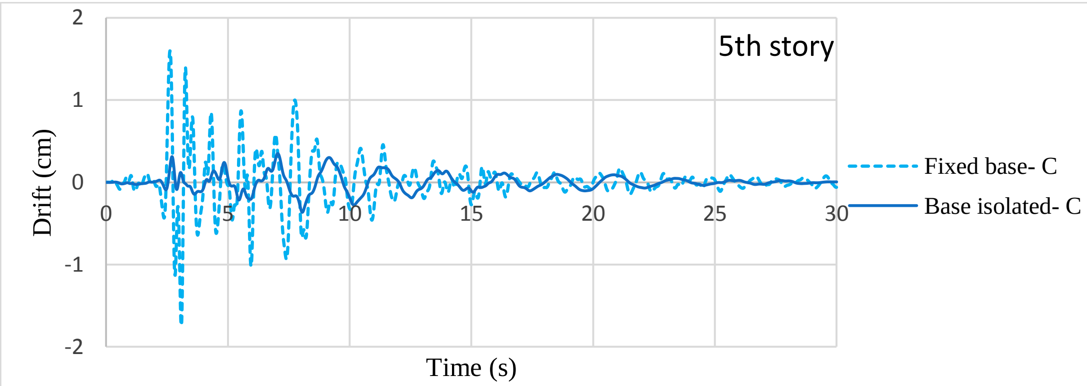


e)

Figure 4.4 Story drift – time history plot of 5 story model under Corralitos earthquake

4.1.2 Northridge (N) earthquake loaded on 5 story building

As in the previous case, nonlinear time history analysis has been done by loading Northridge (N) earthquake force. Where, the aim of using more than one earthquake is to know the effect of changing the strength of the earthquake motion with time on the building, as each earthquake has different characteristics than the other. The results of this case in Figure 4.5 indicated that the maximum relative displacement were decreased from 11 cm for a fixed base building to 2.5 cm in the base isolated building. Likewise, inter-story drift ratio with the storey height has been observed in Figure 4.6. It had a maximum value as 0.88% in fixed base building, while in the building of the base isolated case, it was 0.37%. The relative displacement between the displacement of roof and base, according to time of earthquake motion, that gives an impression about the response of the structure and the safety. It had a low level when using the base isolated as shown in Figure 4.7. Drift with time for each storey were shown in Figure 4.8. As expected, the drifts were reduced when the isolated base was used in the building, indicating a safer building against the seismic motion.

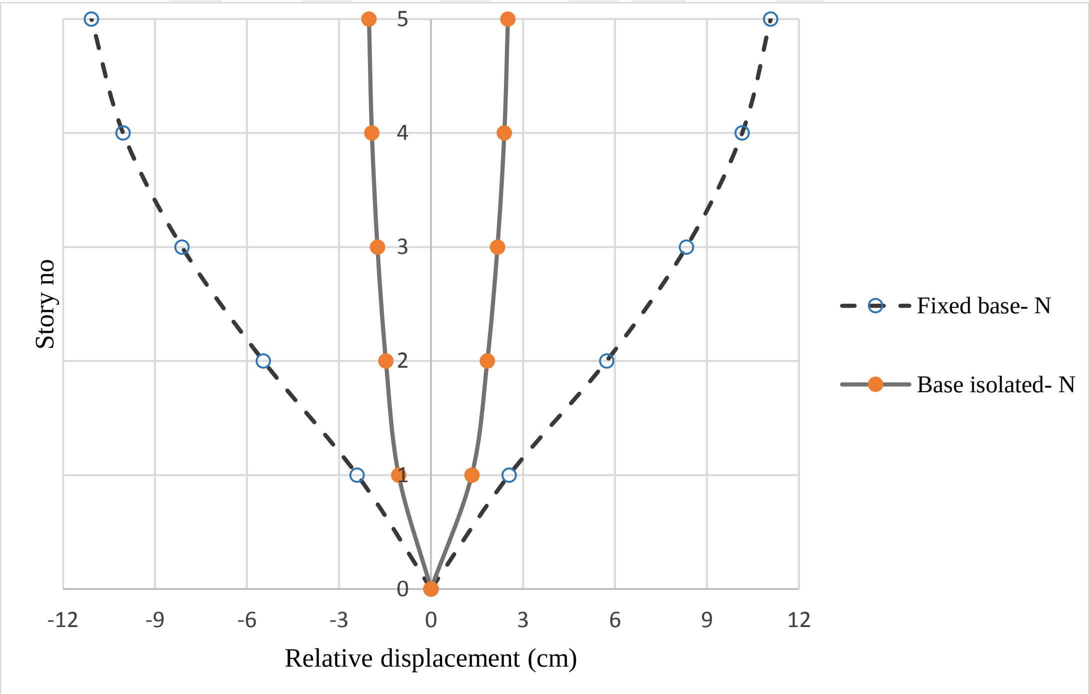


Figure 4.5 Relative displacement for 5 story model with fixed base and base isolation under Northridge earthquake

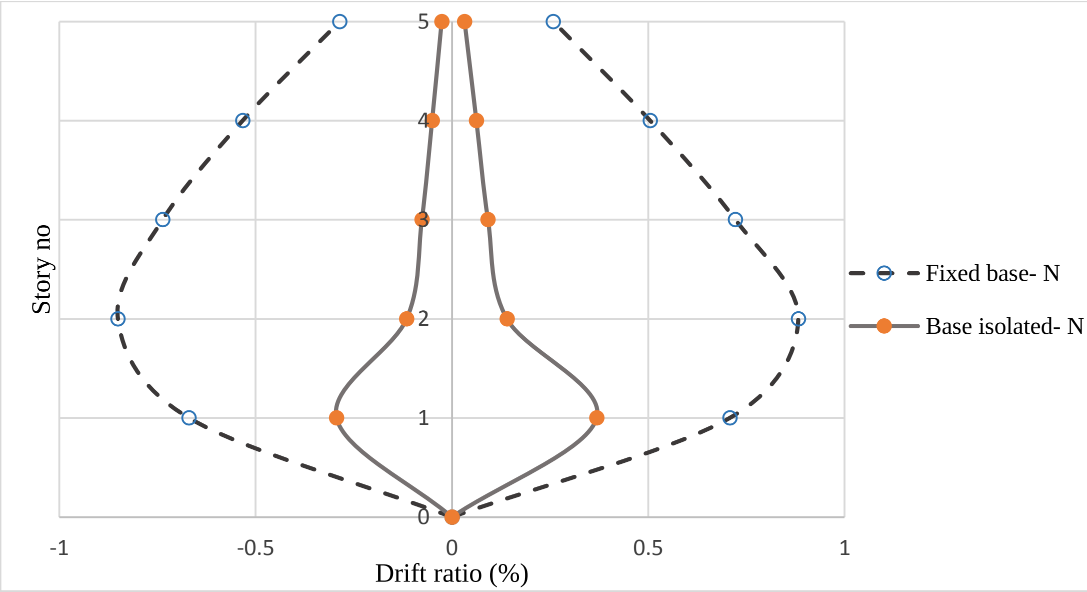


Figure 4.6 Drift ratio for 5 story model with fixed base and base isolation under Northridge earthquake

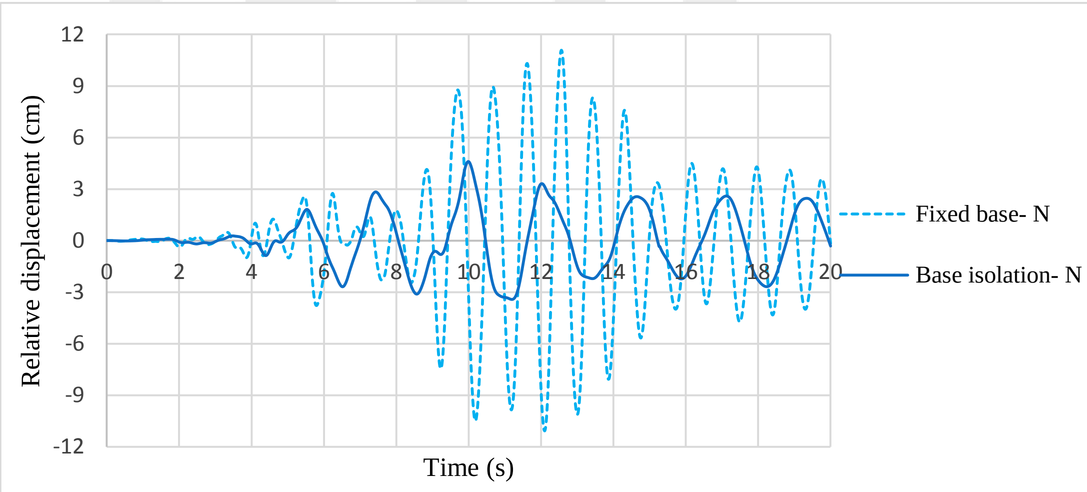
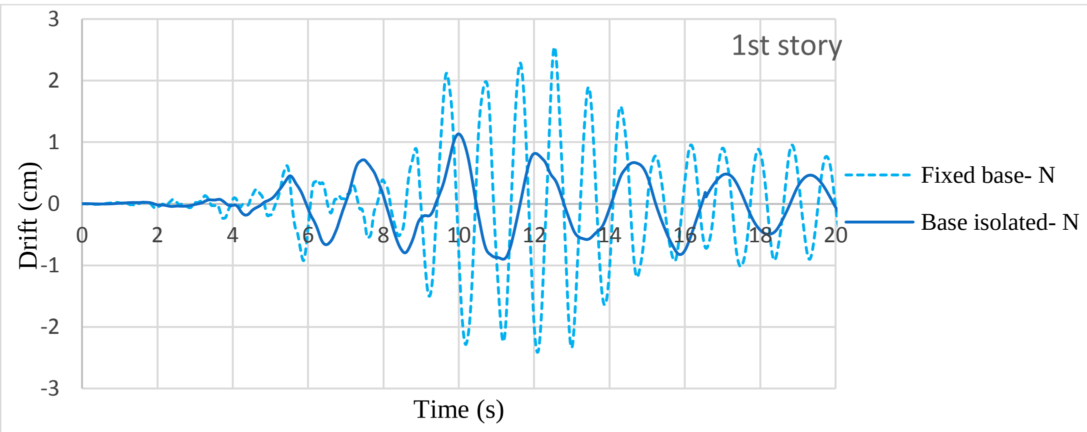
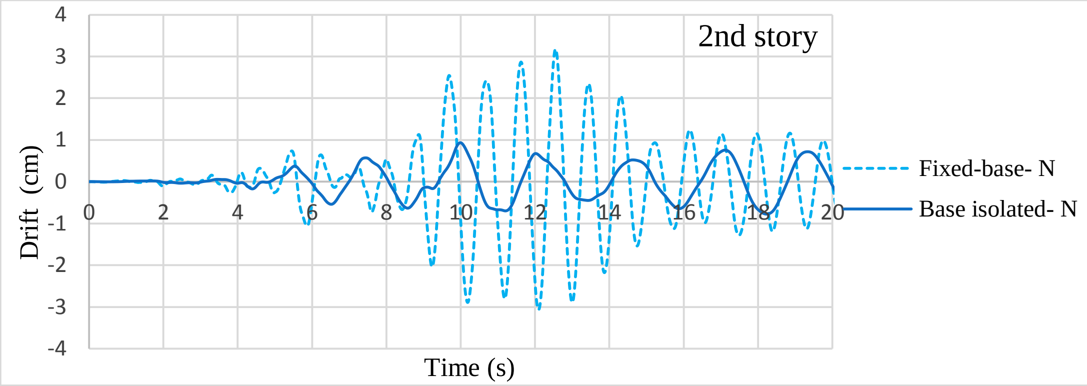


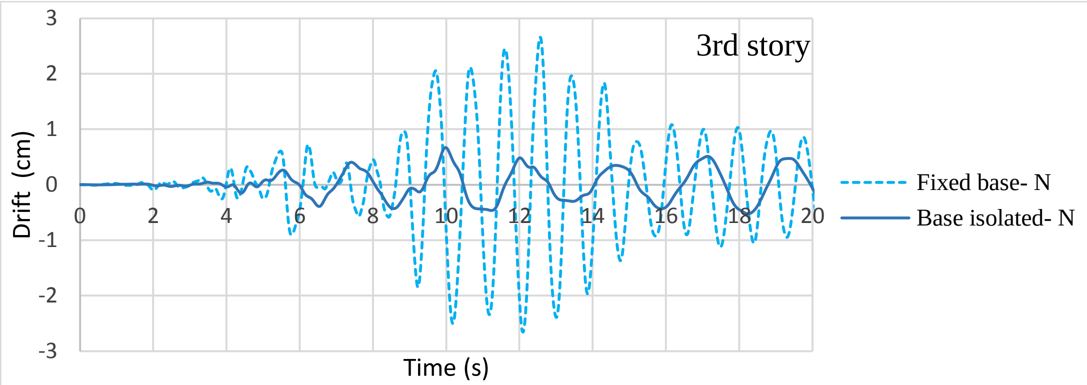
Figure 4.7 Relative roof displacement – time history plot of 5 story model under Northridge earthquake



a)



b)



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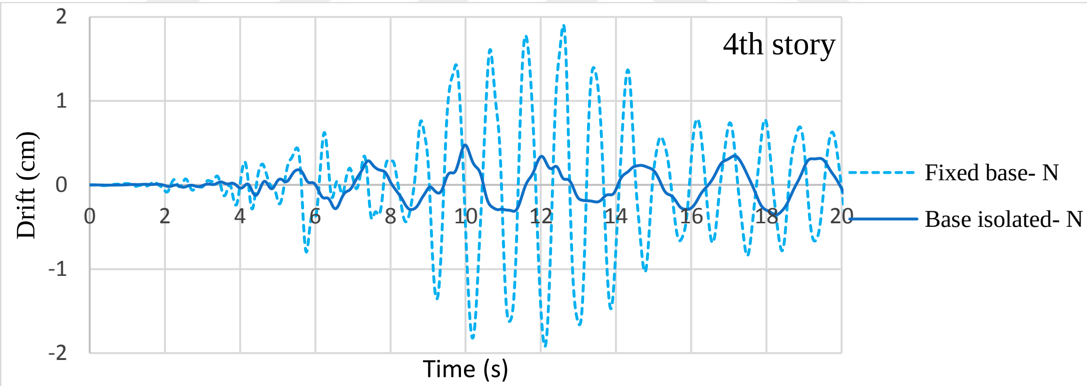

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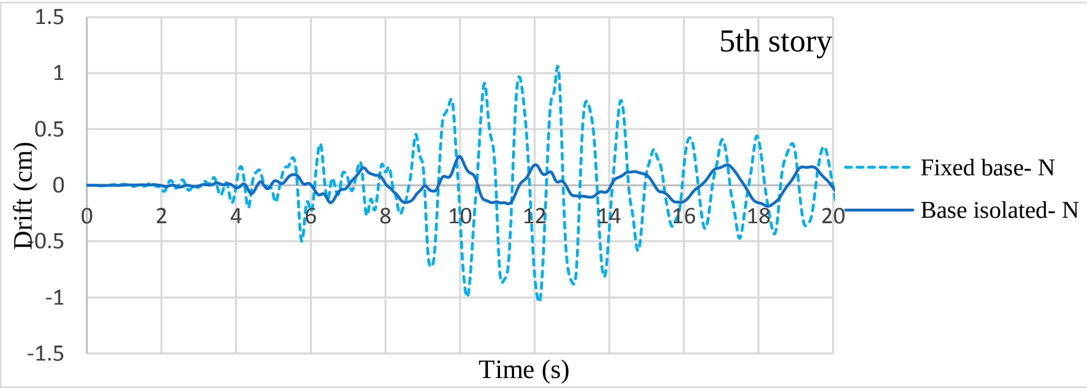


e)

Figure 4.8 Story drift – time history plot of 5 story model under Northridge earthquake

4.1.3 Santa Monica (SM) earthquake loaded on 5-story building

In the same way above, a nonlinear time history analysis was performed using the force of the Santa Monica earthquake. It's clear from the results shown in Figure 4.9, the effect of using the base isolated on relative displacement for storey, where, the maximum relative displacement at the roof of the building have a value 2.2 cm when using the isolated base, while its value at the same point was 8.3 cm for fixed base building. Moreover, the variation of drift ratio in this case for each story shown in Figure 4.10. It was observed that the maximum drift ratio, when using the base isolated, was 0.33% at the first story, while the maximum drift ratio for building having the fixed base was 0.64% at the second story. Furthermore, the relative displacement between the roof and the base of building is an important indicator of the benefits of the using a base isolated in reducing the response of the building to the earthquake motion and the survival of the building as far as possible in a vertical position and avoid inclined on a side. The results of this case are shown in Figure 4.11. Likewise, the drift inter-storey with time was observed in Figure 4.12, which shows that the value of drift decreases when the isolated base is used, and its reduction is more pronounced with increase the height of the building. That indicates a decrease in the swing of the building due to the earthquake motion, and increase the safety factor, in the case of using the base isolation.

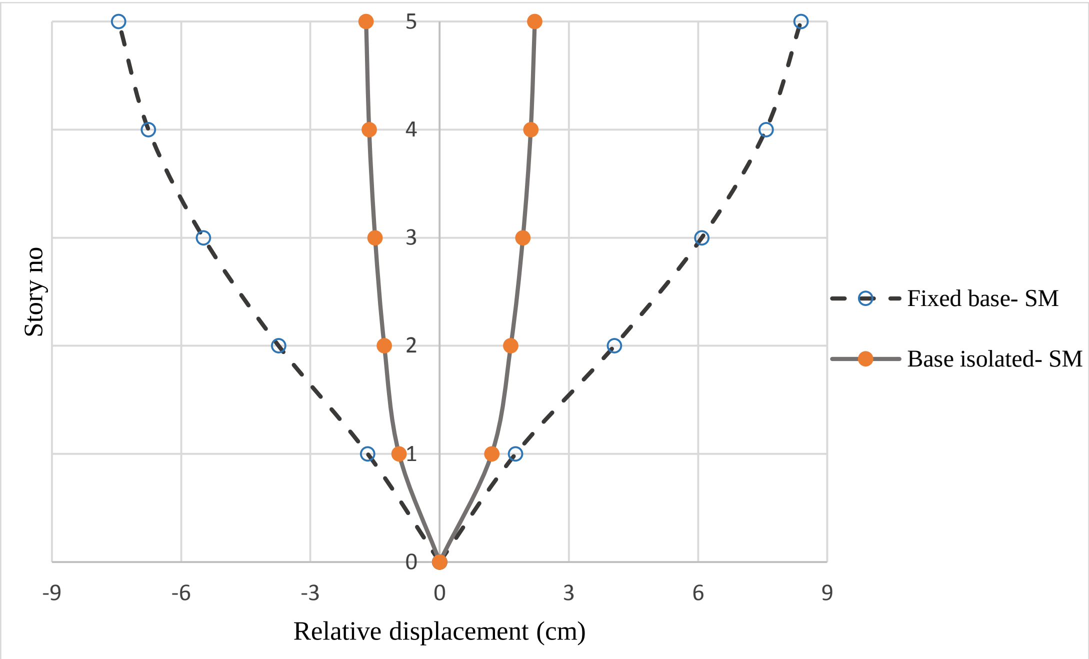


Figure 4.9 Relative displacement for 5 story model with fixed base and base isolation under Santa Monica earthquake

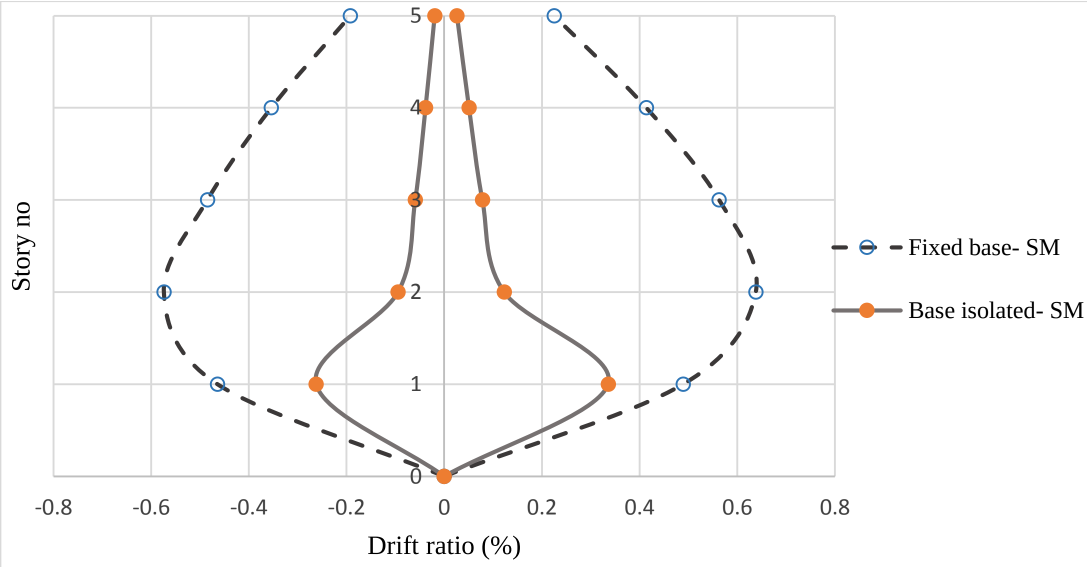


Figure 4.10 Drift ratio for 5 story model with fixed base and base isolation under Santa Monica earthquake

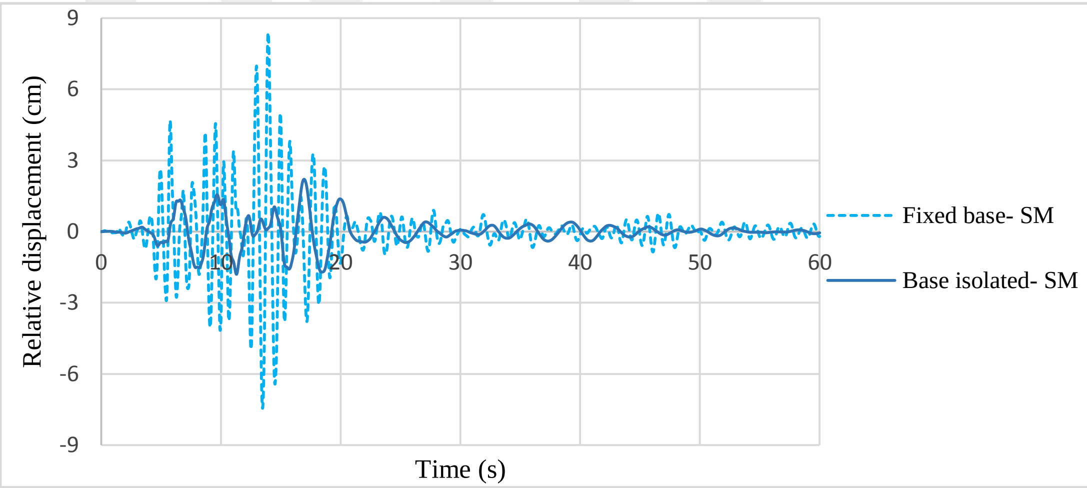
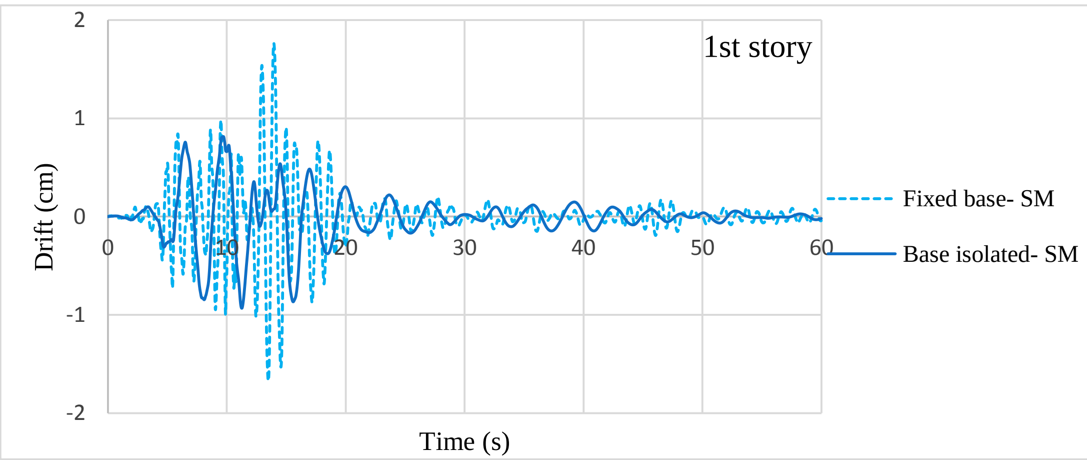
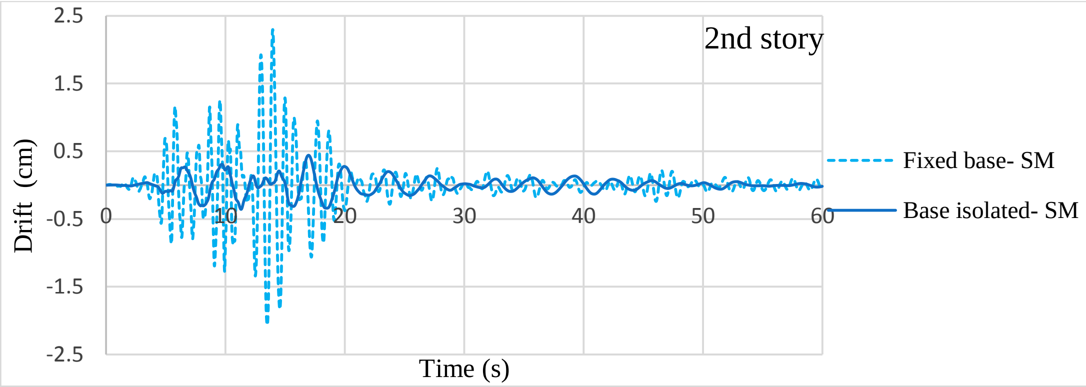


Figure 4.11 Relative roof displacement – time history plot of 5 story model under Santa Monica earthquake



a)



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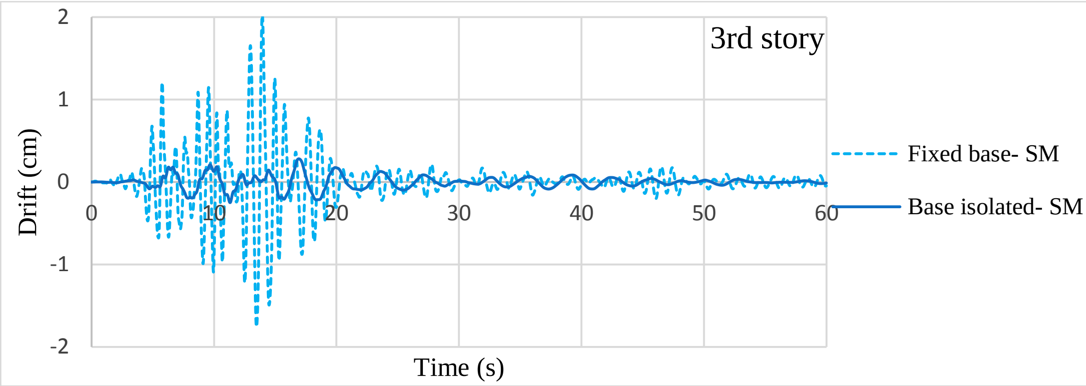

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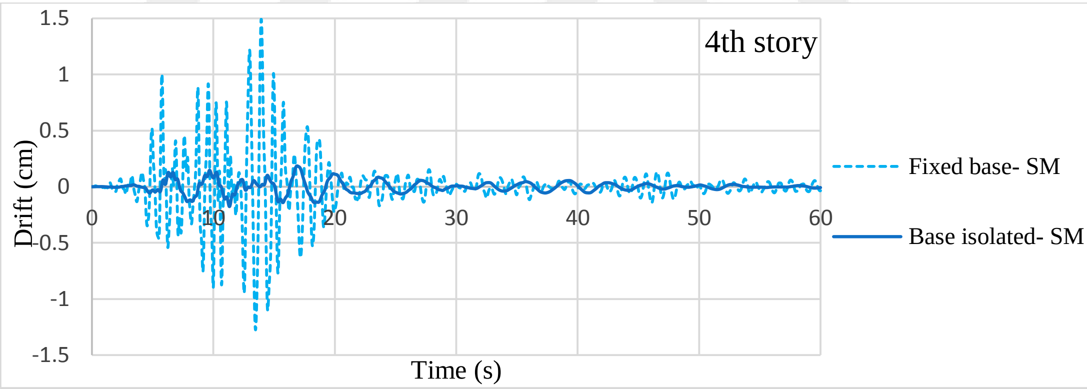

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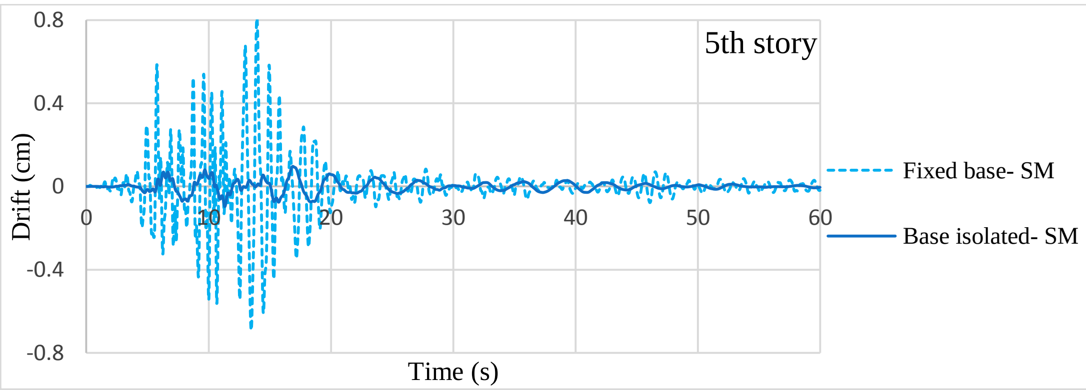


e)

Figure 4.12 Story drift – time history plot of 5 story model under Santa Monica earthquake

4.2 Analysis results of 10-story buildings

The design of the 10 - story building has been done by the same characteristic of 5-story building, with increase the load on a bearing by increase story number, in order to study the effect of the overweight on the properties of isolation. It has been observed that the amount of effective stiffness and post yield stiffness has decreased with increasing load, while the yield strength was increased. Moreover, the time period was increased by addition number of stories. As mentioned in Table 4.1.

4.2.1 Corralitos (C) earthquake loaded on 10-storey building

The Corralitos seismic force resulted in some different behavior with the fixed base building of the above case (5-story building). The maximum relative displacement was 20 cm at the roof while, the maximum relative displacement for the base isolated building was value remained almost as close to the previous case (5-story building), where its value equal to 3.3 cm in the same point at the roof. All results are given in Figure 4.13. It’s evident from the Figure the effect of the use of base isolation to decrease the relative displacement. Also from Figure 4.14, it causes decreasing the inter-story drift ratio, where it has a maximum value 0.72% for the building with fixed base, it has been decreased to 0.38% when using base isolation. This makes the building more safety against the earthquake motion.

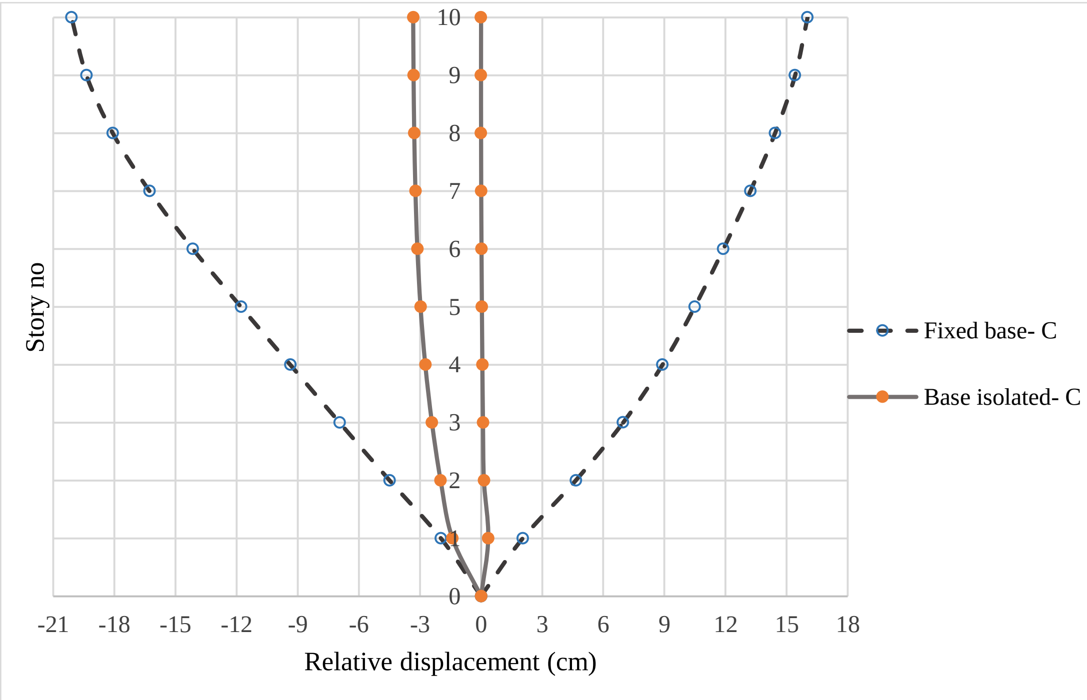


Figure 4.13 Relative displacement for 10 story model with fixed base and base isolation under Corralitos earthquake

Furthermore, the relative displacement between roof and base level with time of the earthquake in Figure 4.15 exhibited a good indication of reducing the response of the building has with isolation. In addition to this, the inter-story drift for each floor is given in Figure 4.16, which shows the difference between the use of the isolated base and the fixed base in the ten-story building, where it is pointed out that the amount of building vibration when using the isolated base is much less than the vibration of the building with the fixed base.

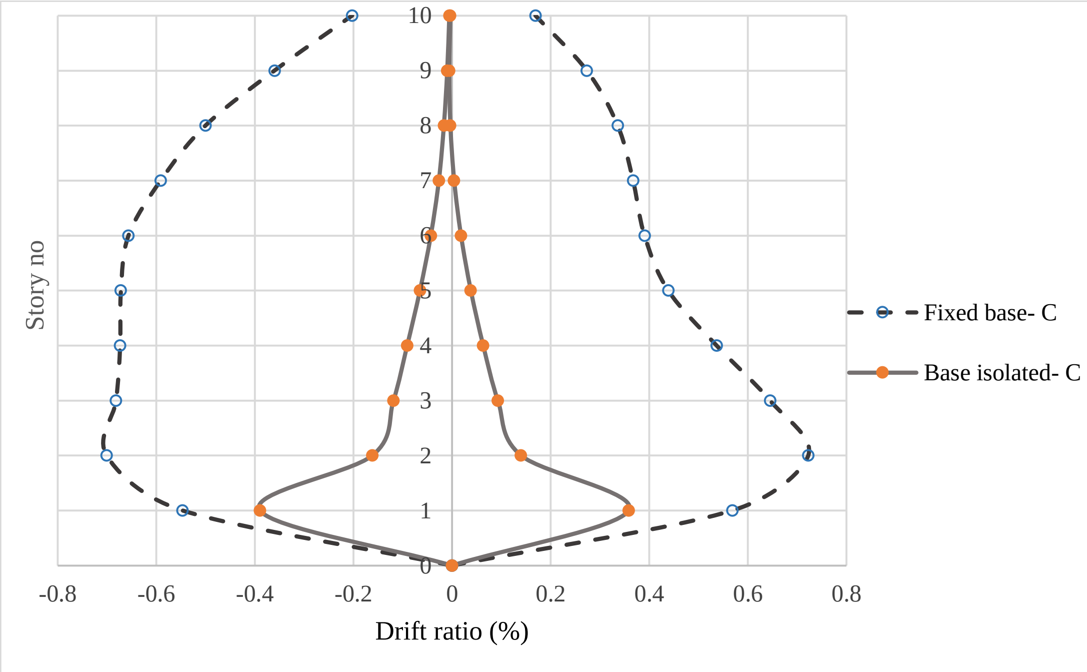


Figure 4.14 Drift ratio for 10 story model with fixed base and base isolation under Corralitos earthquake

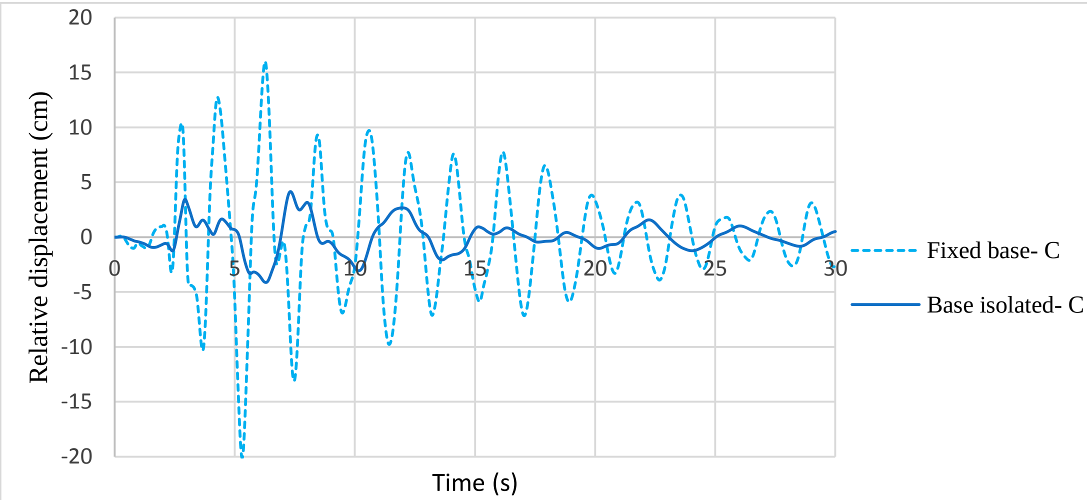
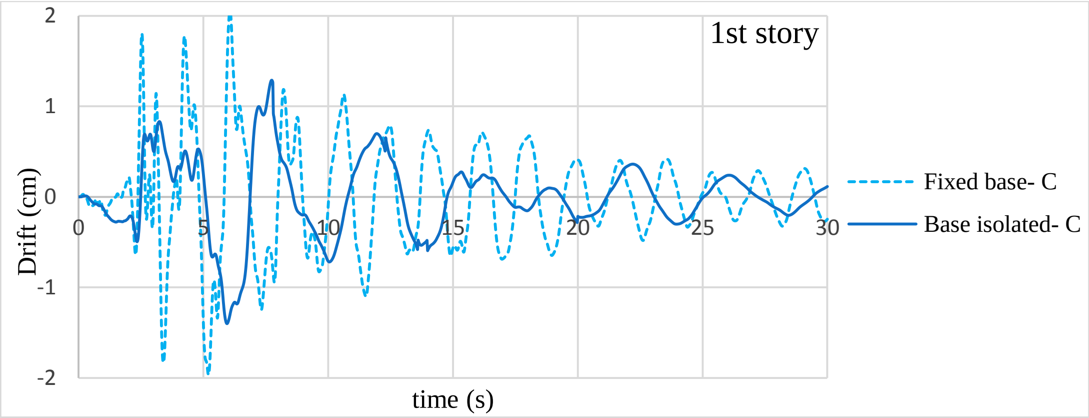
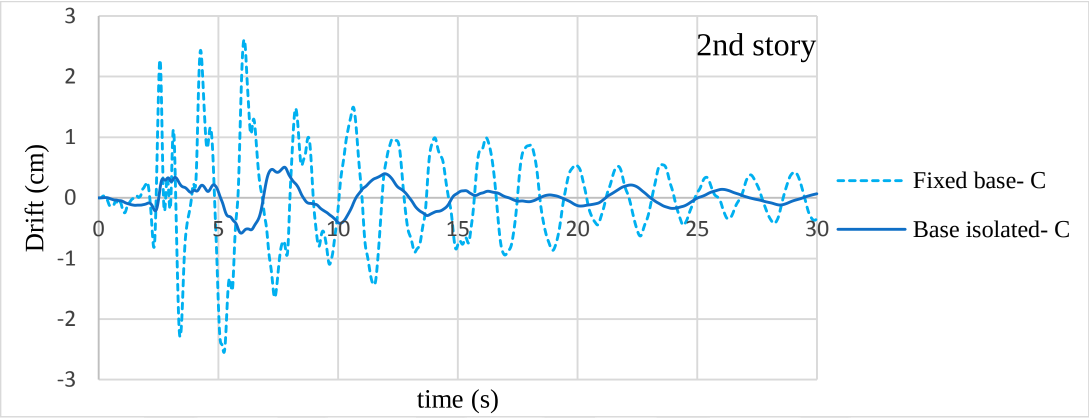


Figure 4.15 Relative roof displacement – time history plot of 10-storey model under Corralitos earthquake



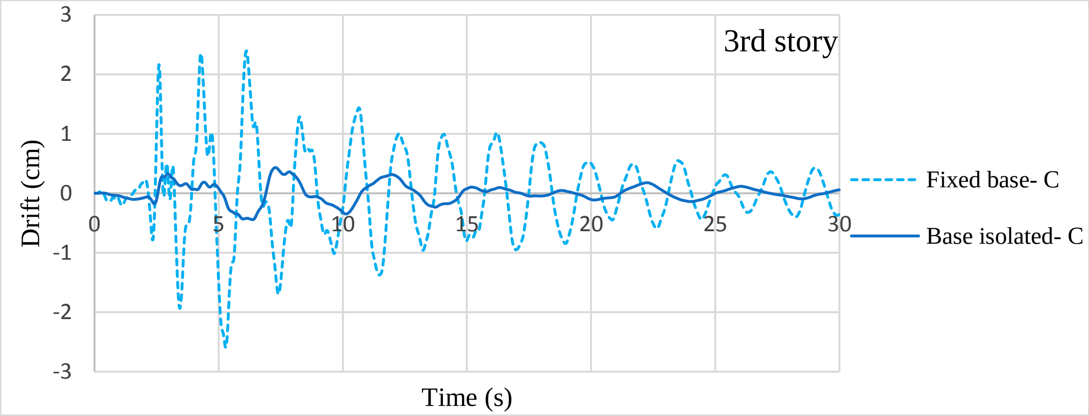
1st story
Drift (cm)
time (s)
Fixed base- C
Base isolated- C

a)



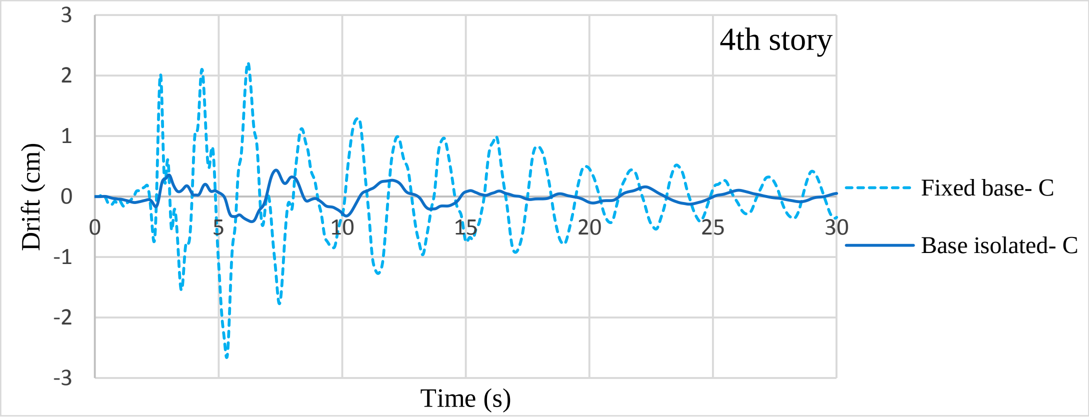
2nd story
Drift (cm)
time (s)
Fixed base- C
Base isolated- C

b)



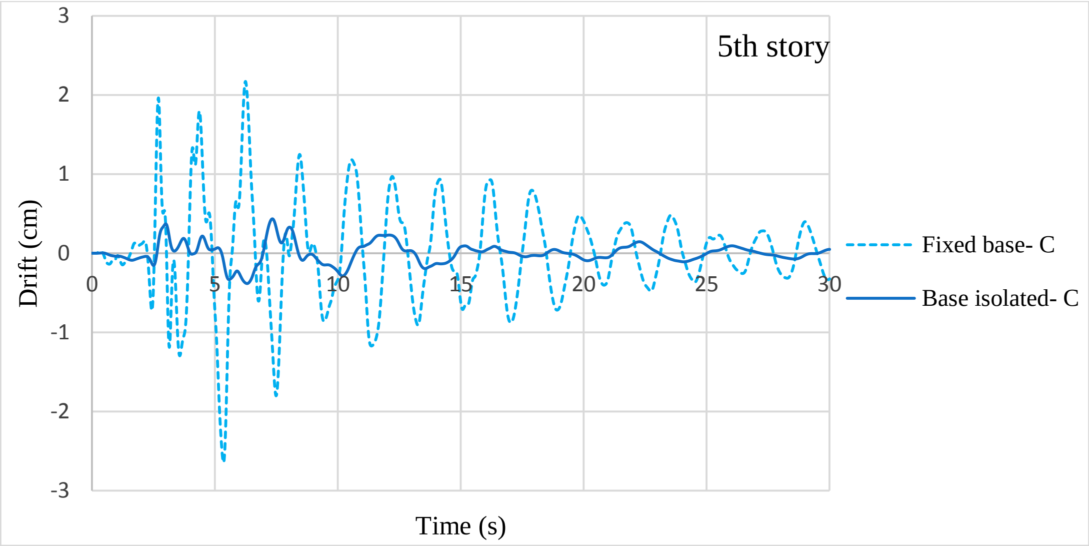
3rd story
Drift (cm)
Time (s)
Fixed base- C
Base isolated- C

c)

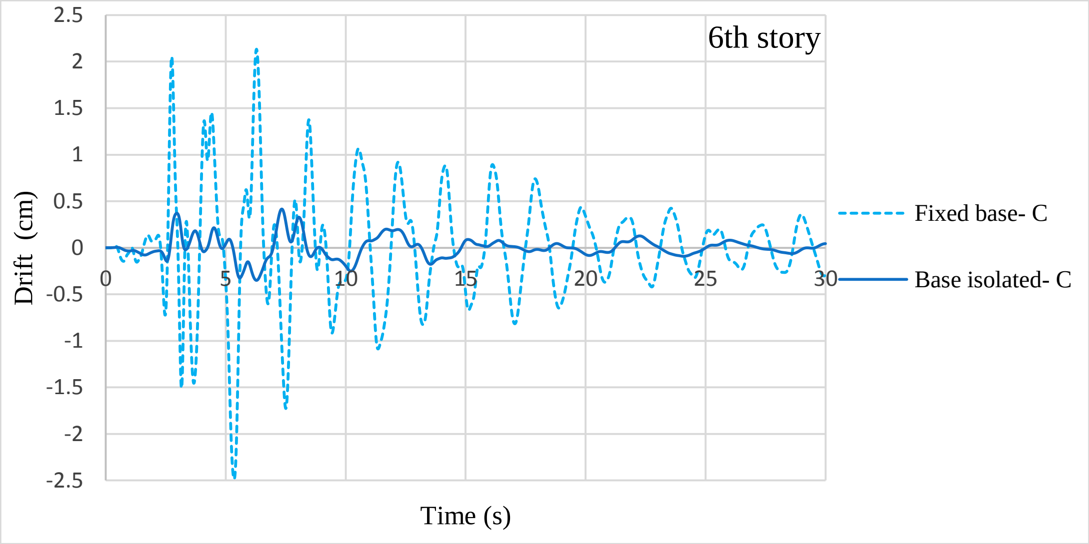


4th story
Drift (cm)
Time (s)
Fixed base- C
Base isolated- C

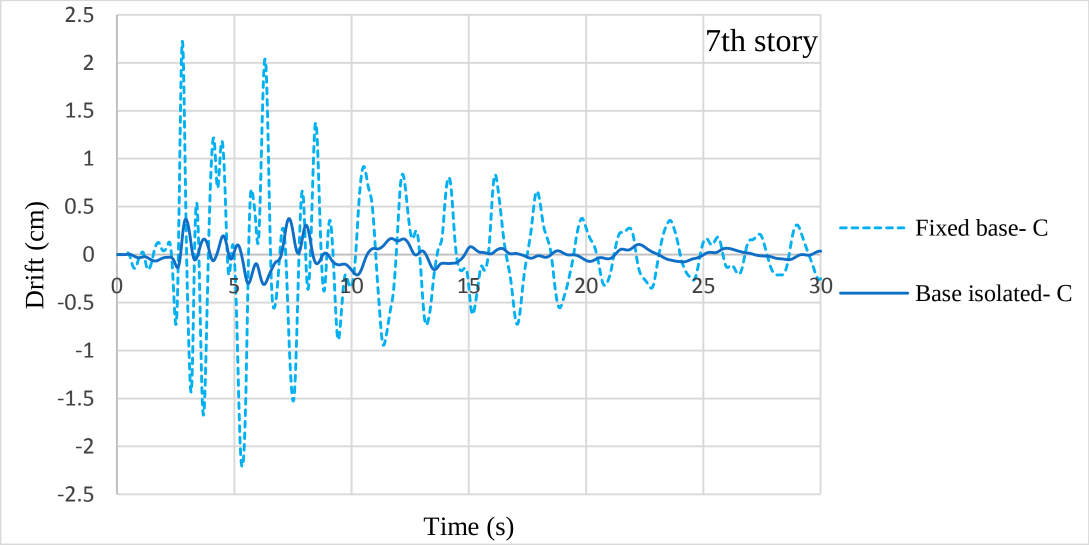
d)


5th story
Drift (cm)
Time (s)
3
2
1
0
-1
-2
-3
0
5
10
15
20
25
30
Fixed base- C
Base isolated- C

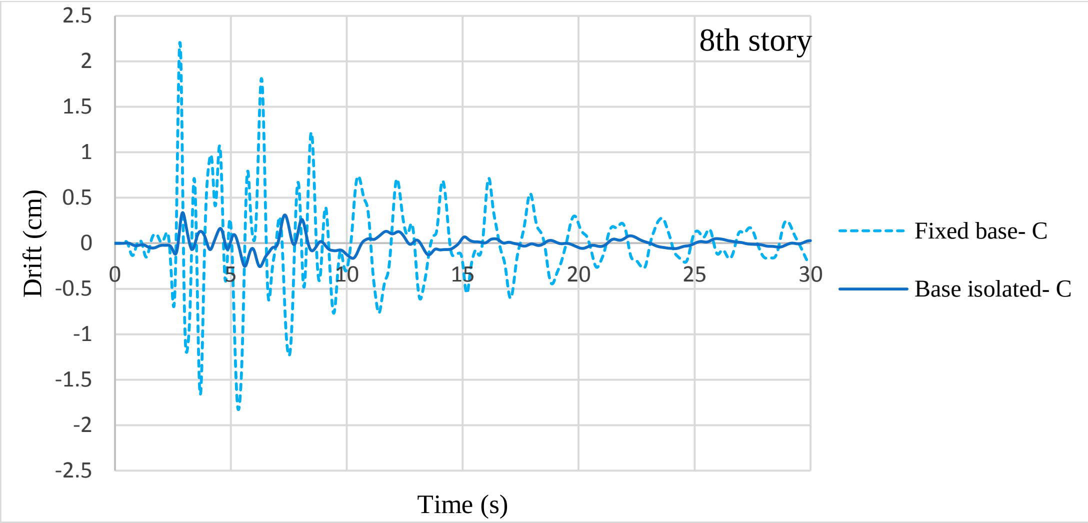
e)


6th story
Drift (cm)
Time (s)
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
0
5
10
15
20
25
30
Fixed base- C
Base isolated- C

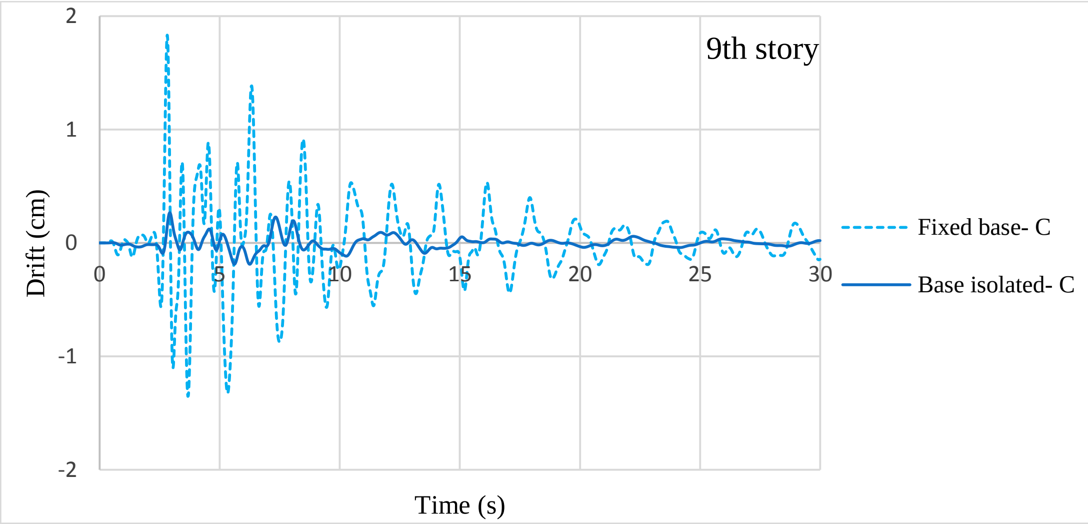
f)


7th story
Drift (cm)
Time (s)
2.5
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
0
5
10
15
20
25
30
Fixed base- C
Base isolated- C

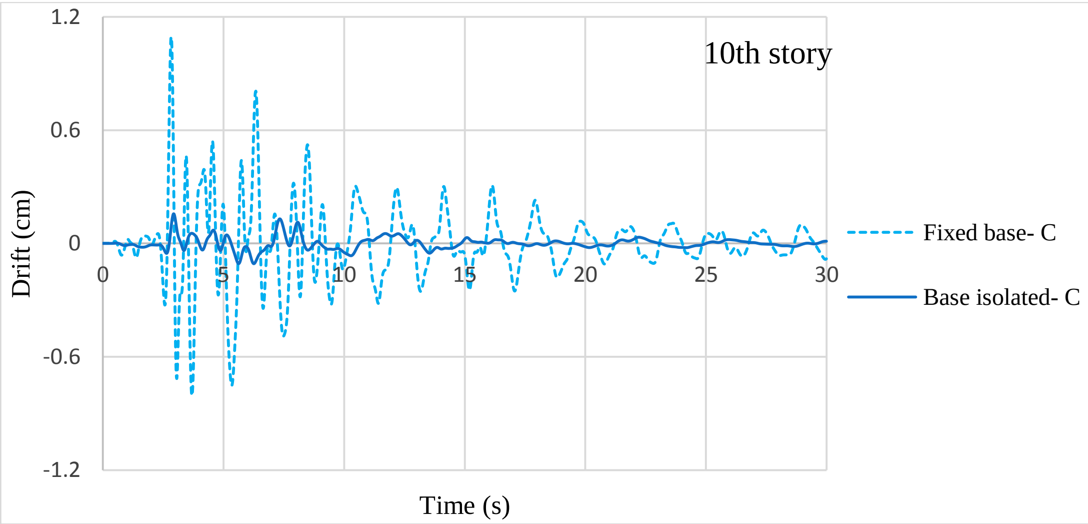
g)



h)



i)



j)

Figure 4.16 Story drift – time history plot of 10 story model under Corralitos earthquake

4.2.2 Northridge (N) earthquake loaded on 10-story building

Similar to the previous approach, the Northridge earthquake force was carried out on a 10-story building, but in that case a larger time has been taken for the earthquake motion. It is worth noting that the maximum relative displacement in the fixed base building and the base isolated building hasn't changed much from the previous case (for 5-story building). Where it was value 12.25 cm with fixed base building and 2.29 cm with isolated base building. So it is due to the building's response to the characteristics of the earthquake, as in Figure 4.17. The inter-story drift ratio has some variation when increasing building height, especially at high levels where their value is very low, as in Figure 4.18. It was recorded the highest value of 0.5% for fixed base building while the value was 0.19% when an isolated base was used in the building. This gives more safety for construction and reduces the stresses on building elements under the influence of the earthquake motion. Additionally, an important index of the building's response is relative displacement with time of the earthquake motion, and inter-story drift with time for each floor. It is delineated in Figures 4.19 and 4.20 that the base isolation has remarkable effect on reduction the building's response and vibration.

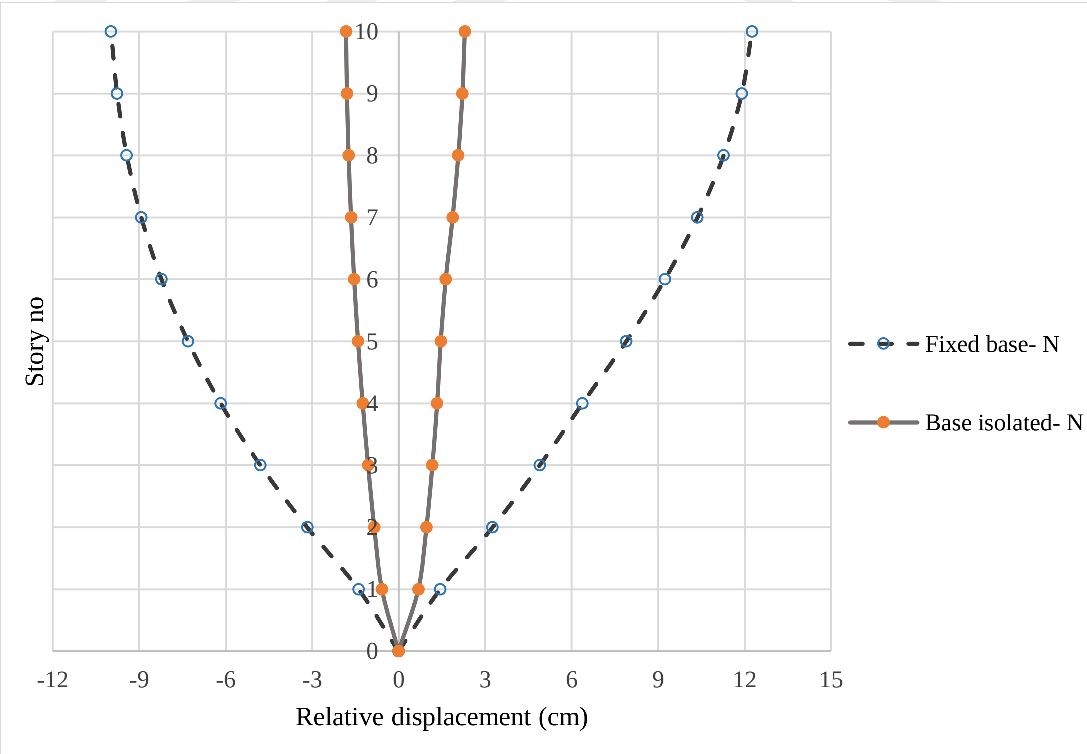


Figure 4.17 Relative displacement for 10 story model with fixed base and base isolation under Northridge earthquake

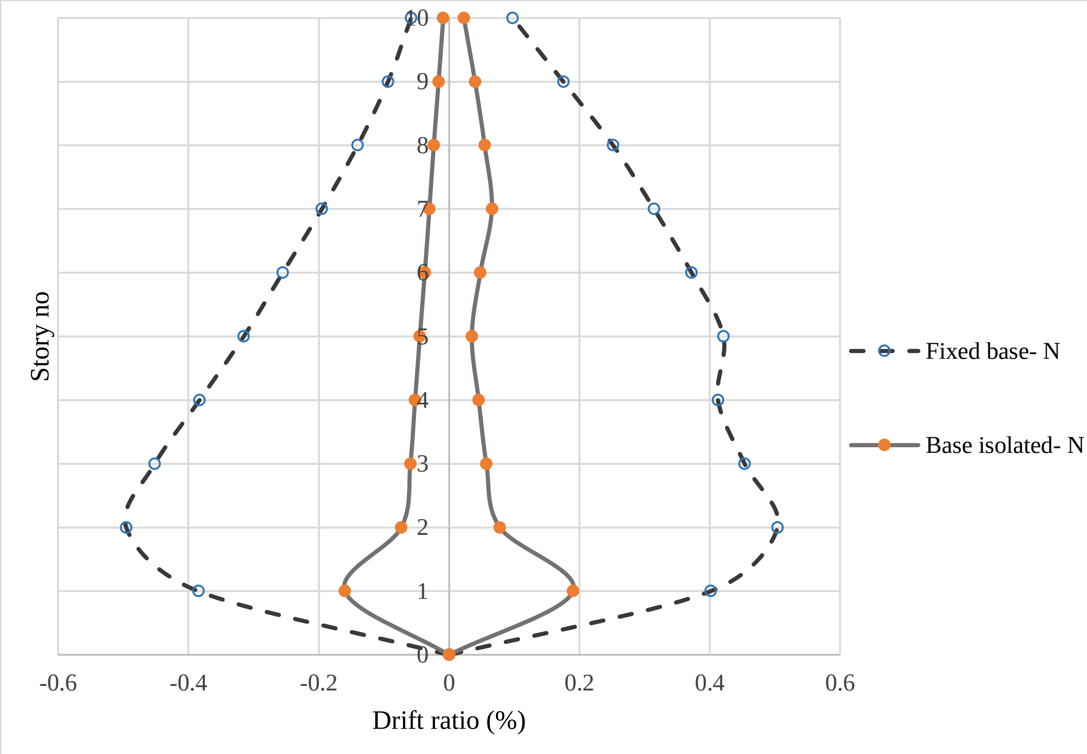


Figure 4.18 Drift ratio for 10 story model with fixed base and base isolation under Northridge earthquake

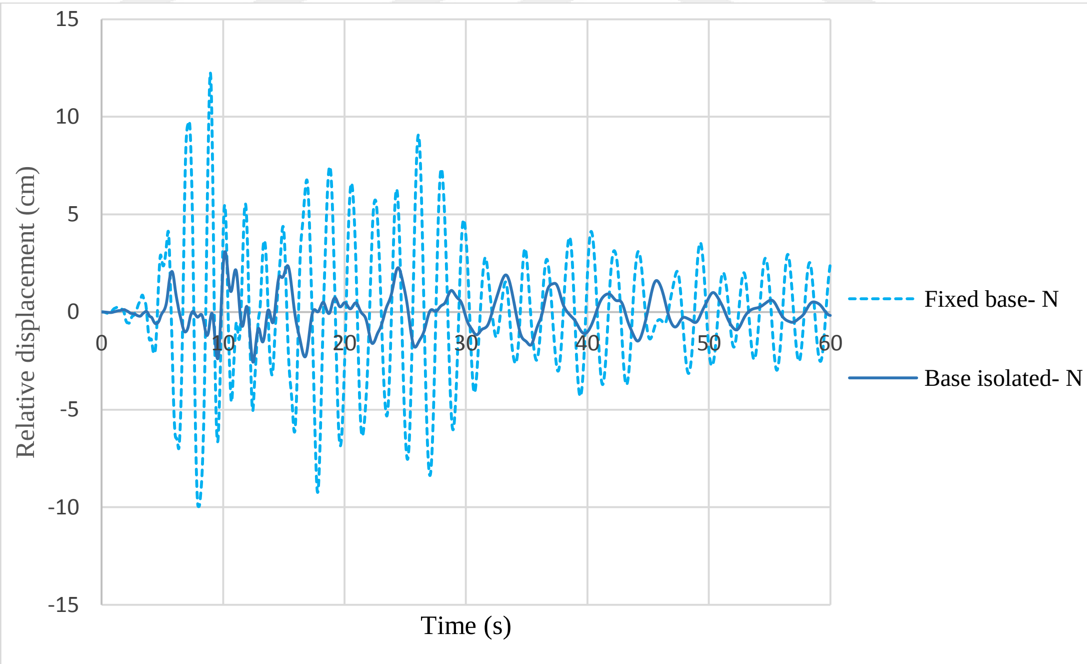
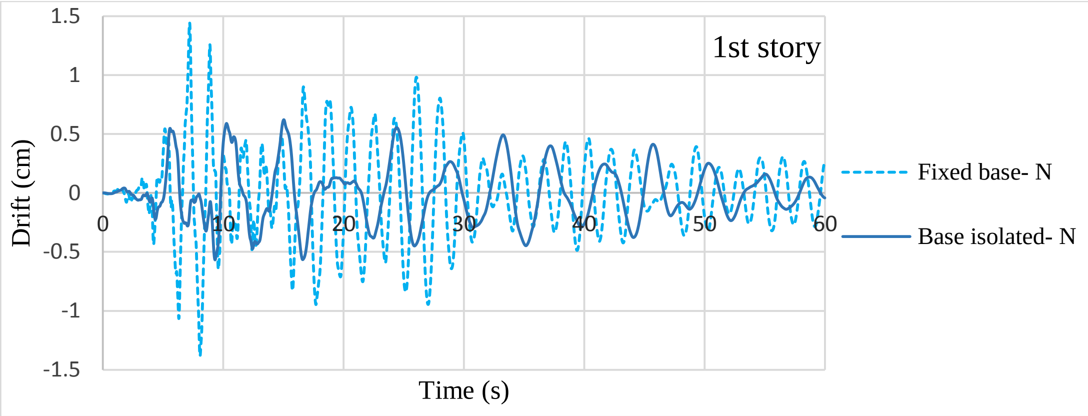
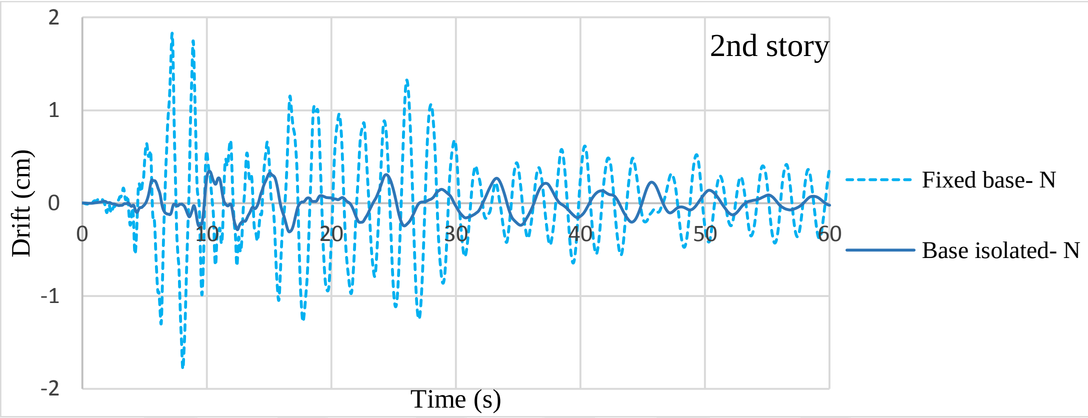


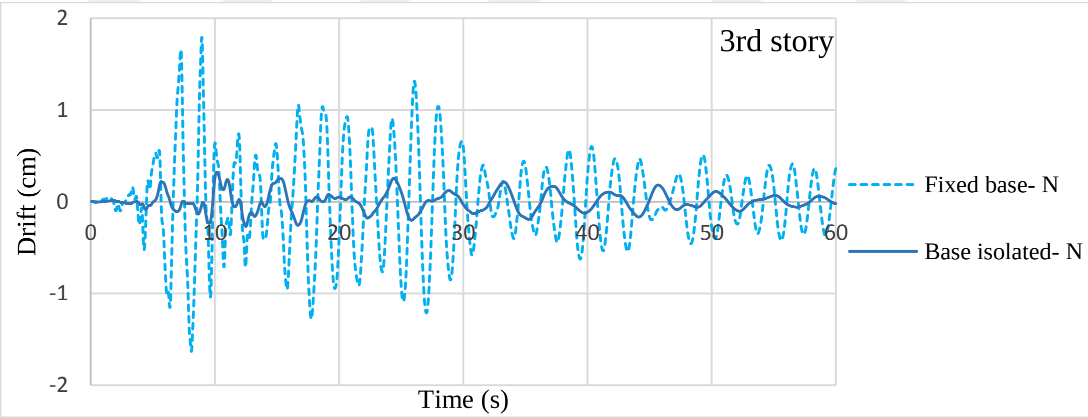
Figure 4.19 Relative roof displacement – time history plot of 10 story model under Northridge earthquake


1st story
Drift (cm)
1.5
1
0.5
0
-0.5
-1
-1.5
0
10
20
30
40
50
60
Time (s)
Fixed base- N
Base isolated- N

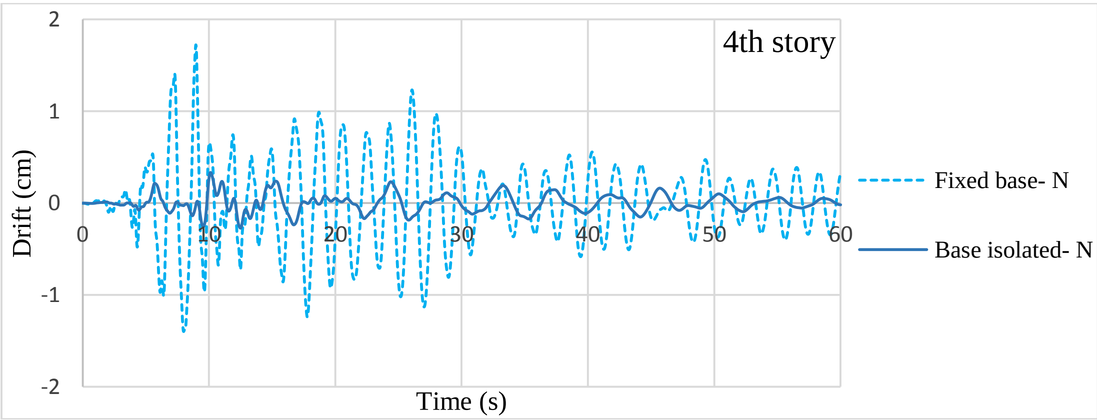
a)


2nd story
Drift (cm)
2
1
0
-1
-2
0
10
20
30
40
50
60
Time (s)
Fixed base- N
Base isolated- N

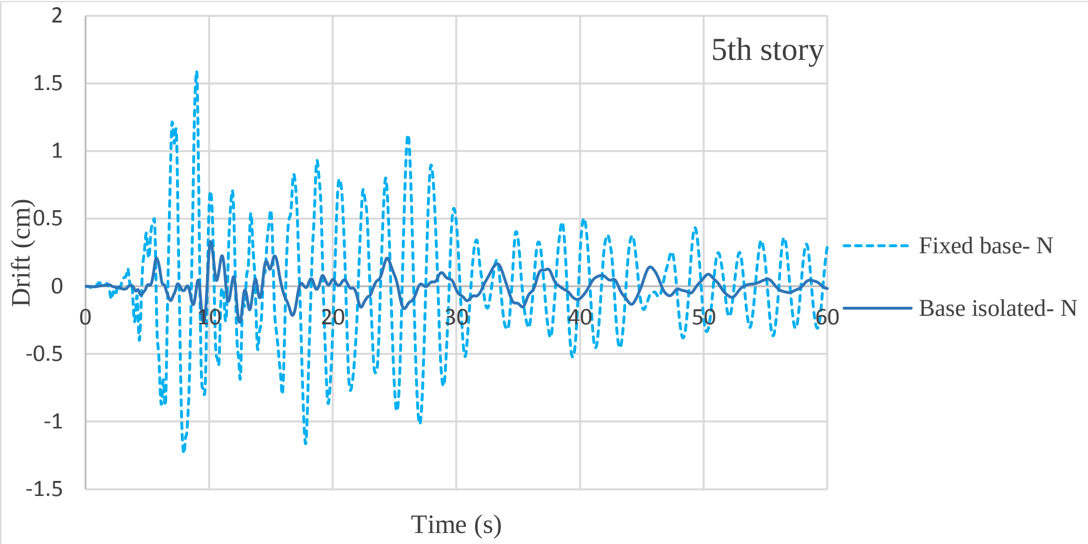
b)


3rd story
Drift (cm)
2
1
0
-1
-2
0
10
20
30
40
50
60
Time (s)
Fixed base- N
Base isolated- N

c)

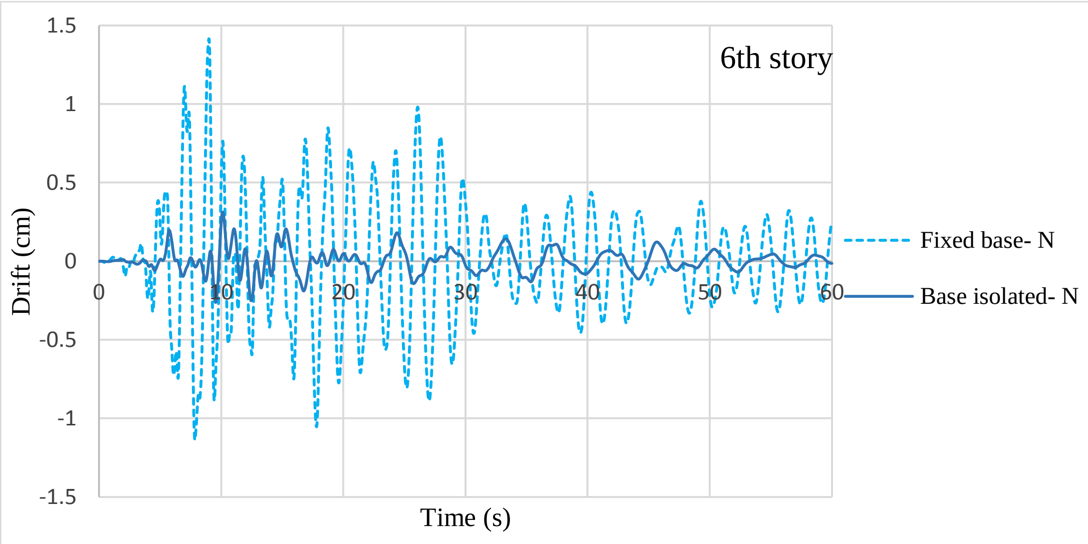

4th story
Drift (cm)
2
1
0
-1
-2
0
10
20
30
40
50
60
Time (s)
Fixed base- N
Base isolated- N

d)



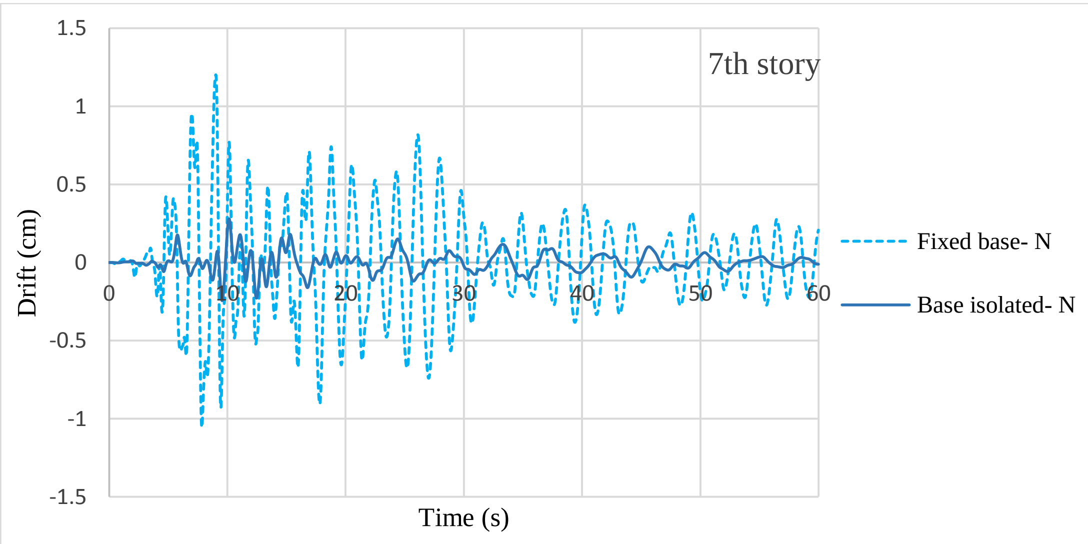
5th story
Drift (cm)
Time (s)
Fixed base- N
Base isolated- N

e)



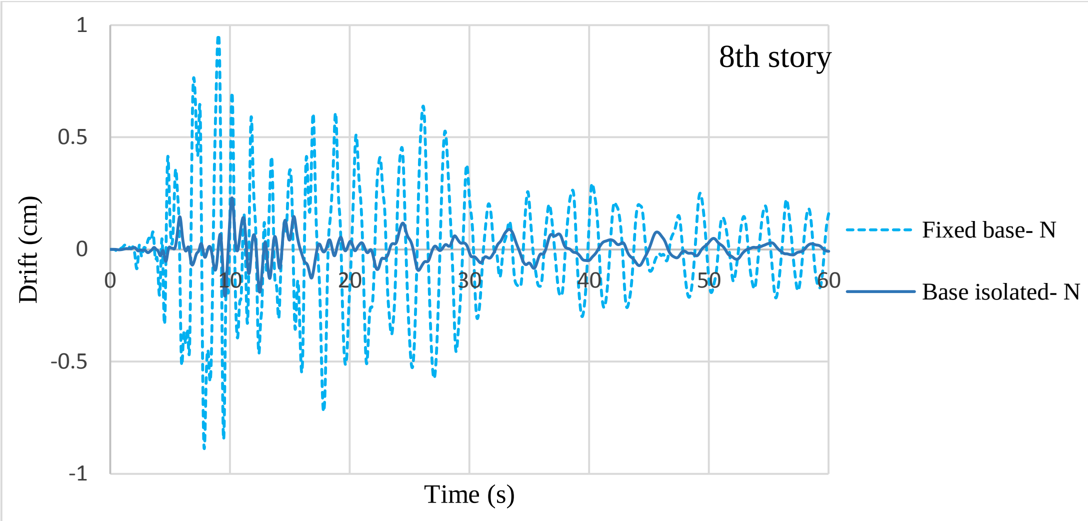
6th story
Drift (cm)
Time (s)
Fixed base- N
Base isolated- N

f)

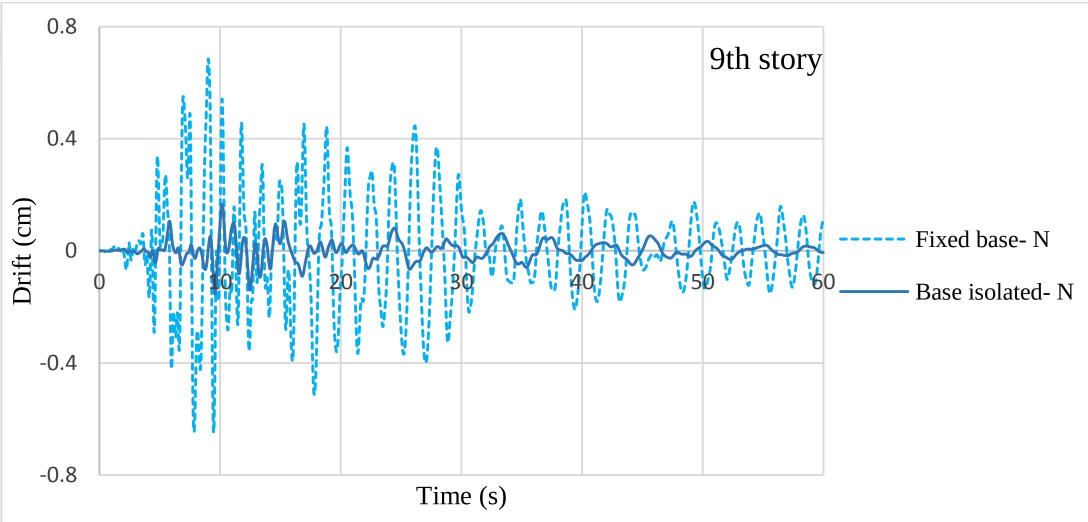


7th story
Drift (cm)
Time (s)
Fixed base- N
Base isolated- N

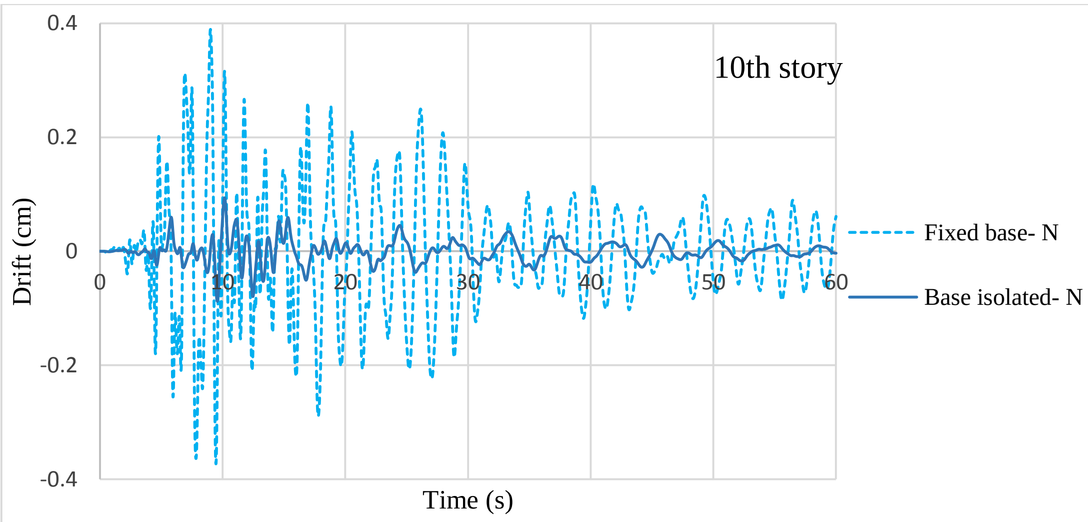
g)



h)



i)



j)

Figure 4.20 Story drift – time history plot of 10 story model under Northridge earthquake

4.2.3 Santa Monica (SM) earthquake loaded on 10-story building

The Santa Monica seismic force is one of the powerful earthquakes, this is evident in Figure 4.21 that the increase of the amount of displacement compared to the other earthquakes mentioned above with a ten-story building. Whereas the use of the isolated base led to reduce the maximum relative displacement from 19.8 cm at the roof level of the fixed base building to 3 cm for the same level of isolated building by the lead rubber isolation system. It is very clear from the figure that the effect of the base isolation in maintaining the building in a vertical position and reduce its tendency due to the earthquake motion. Generally, the result of this is an increase the safety factor of the building in the preservation of the life and equipment of the structure, which is required in this research. The optimum effect of the base isolation was observed on a ten-storey building with the Santa Monica earthquake, where the curve of the inter-storey drift ratio with building height, was appeared smoothly. The results shown in Figure 4.22 indicates the ability of the base isolation to reduce the maximum drift ratio when it's used in the building to 0.25%, after it had a value of 0.75% of the building with fixed base.

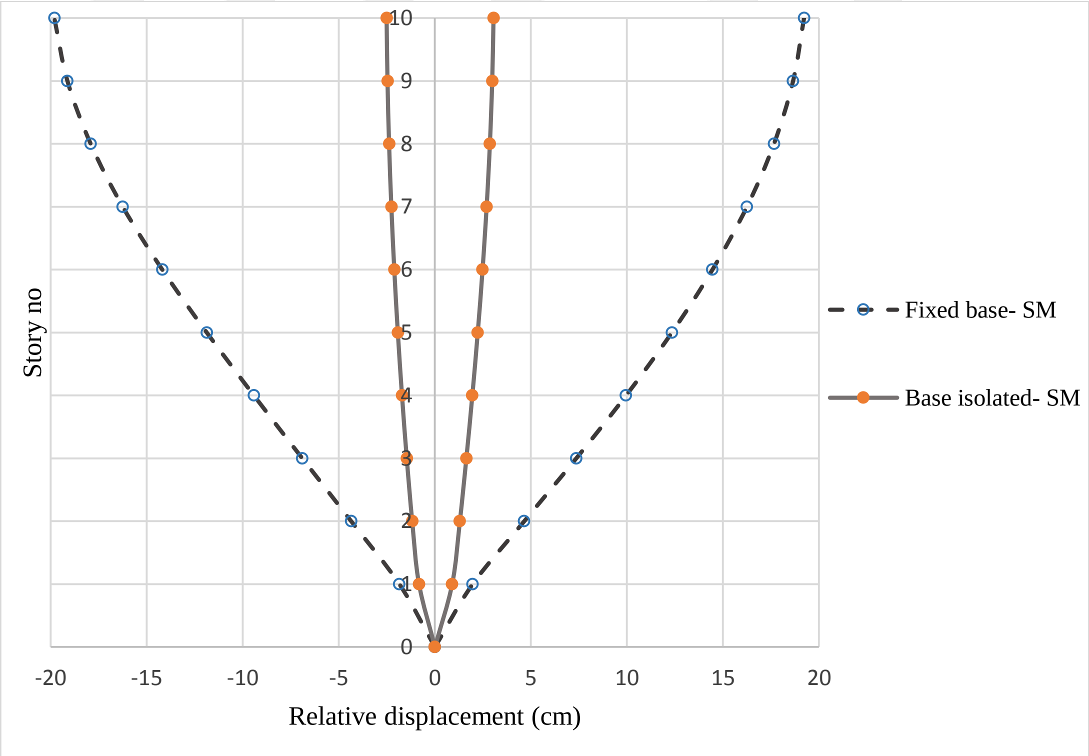


Figure 4.21 Relative displacement for 10 story model with fixed base and base isolation under Santa Monica earthquake

Whereas, the results showed that the relationship between the relative displacement with time of earthquake in Figure 4.23, and the relationship between the inter-story drift with the time in Figure 4.24, indicate clearly that the use of base isolation reduces the building's response to the impact of the earthquake movement. The base isolation works to damping the earthquake and reduce the acceleration force in the building in order to keep the safety of the building and its durability against earthquake attack.

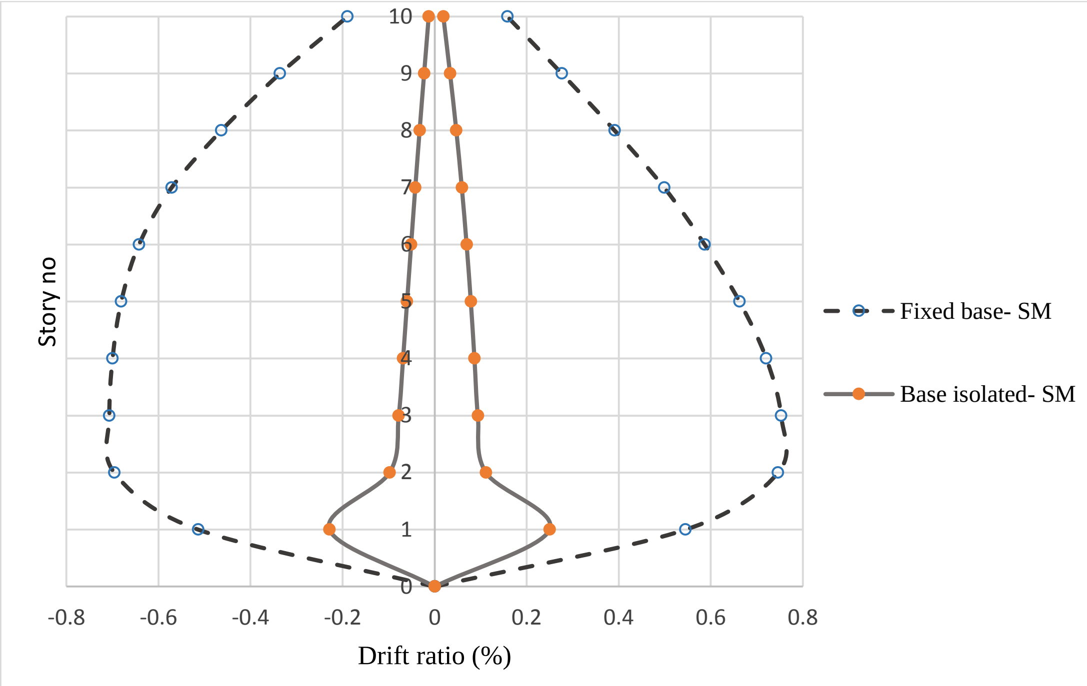


Figure 4.22 Drift ratio for 10 story model with fixed base and base isolation under Santa Monica earthquake

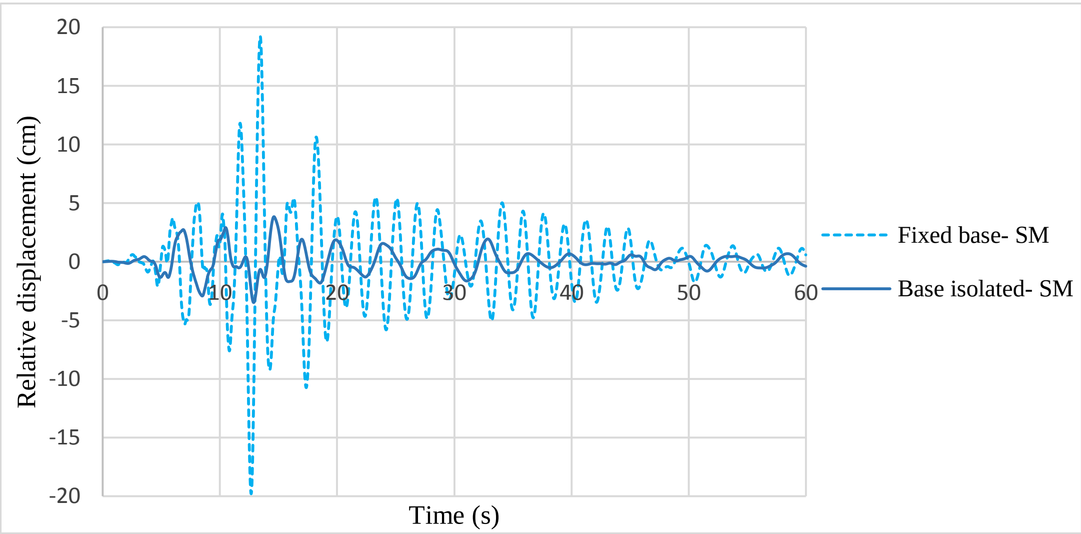
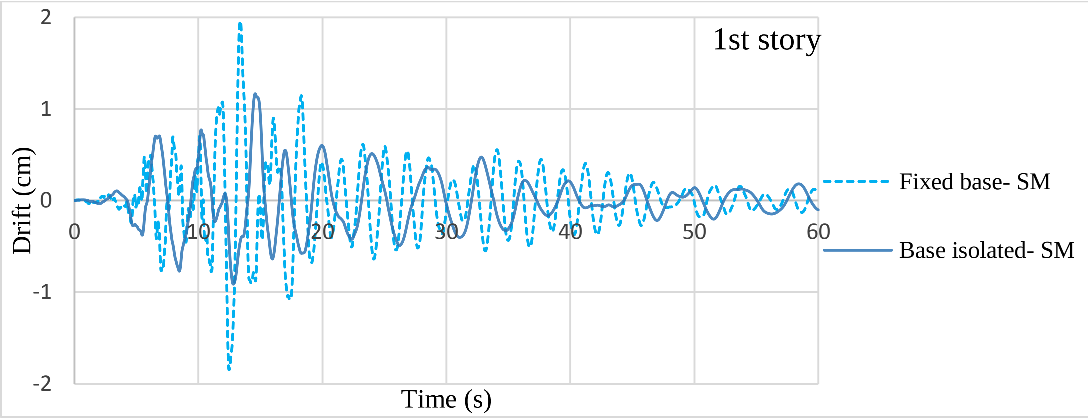
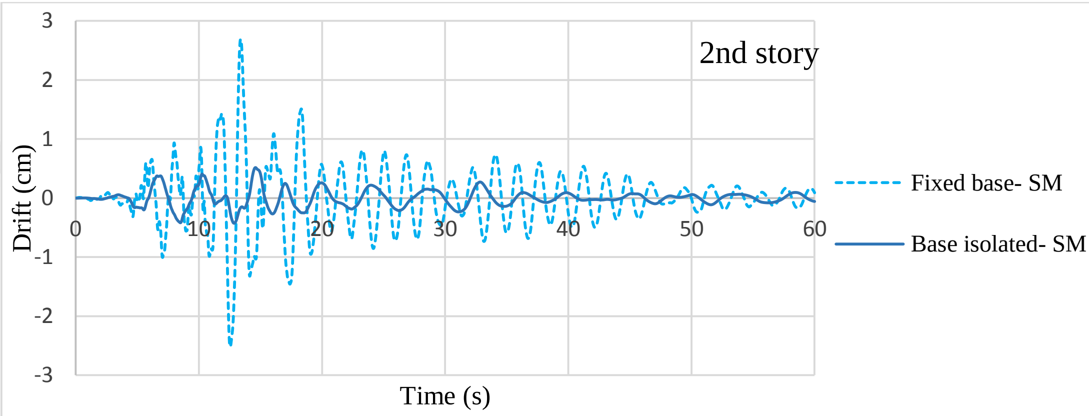


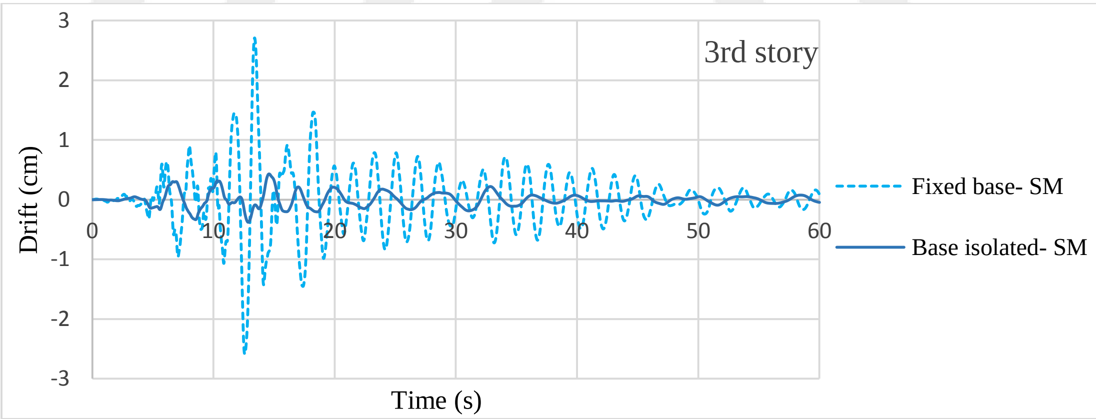
Figure 4.23 Relative roof displacement – time history plot of 10 story model under Santa Monica earthquake


1st story
Drift (cm)
2
1
0
-1
-2
0
10
20
30
40
50
60
Time (s)
Fixed base- SM
Base isolated- SM

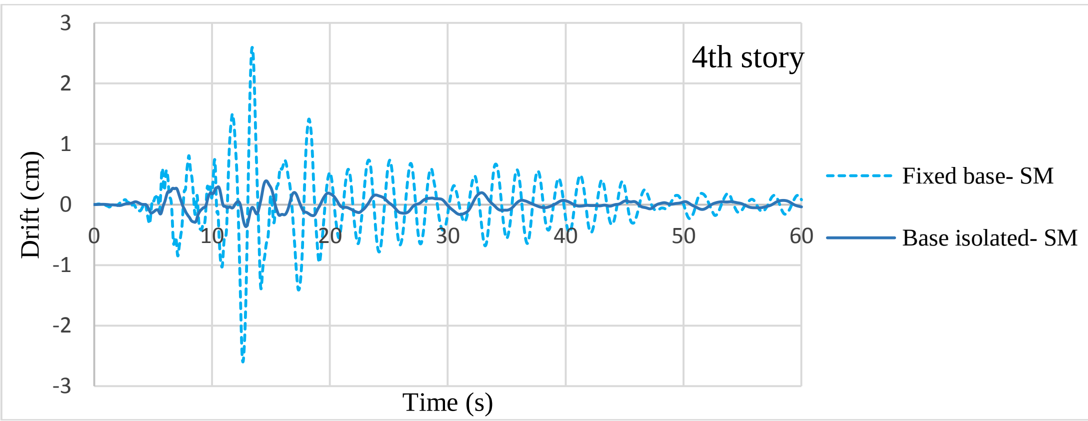
a)


2nd story
Drift (cm)
3
2
1
0
-1
-2
-3
0
10
20
30
40
50
60
Time (s)
Fixed base- SM
Base isolated- SM

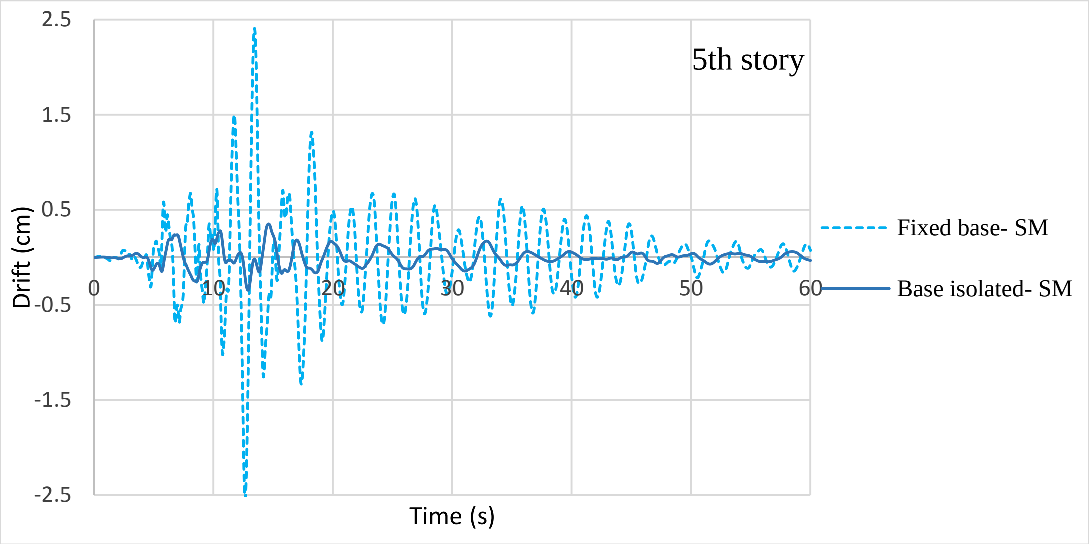
b)


3rd story
Drift (cm)
3
2
1
0
-1
-2
-3
0
10
20
30
40
50
60
Time (s)
Fixed base- SM
Base isolated- SM

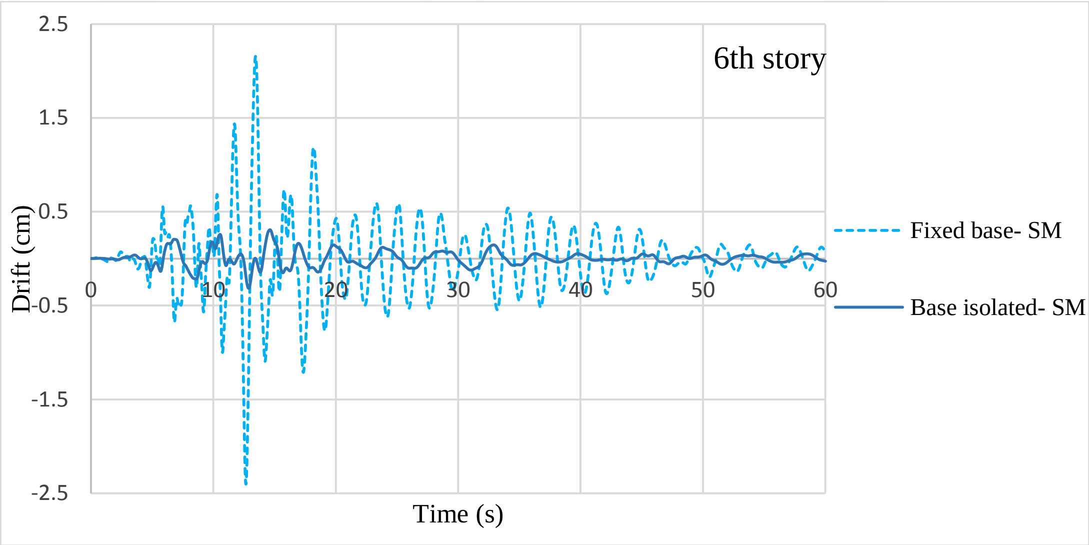
c)


4th story
Drift (cm)
3
2
1
0
-1
-2
-3
0
10
20
30
40
50
60
Time (s)
Fixed base- SM
Base isolated- SM

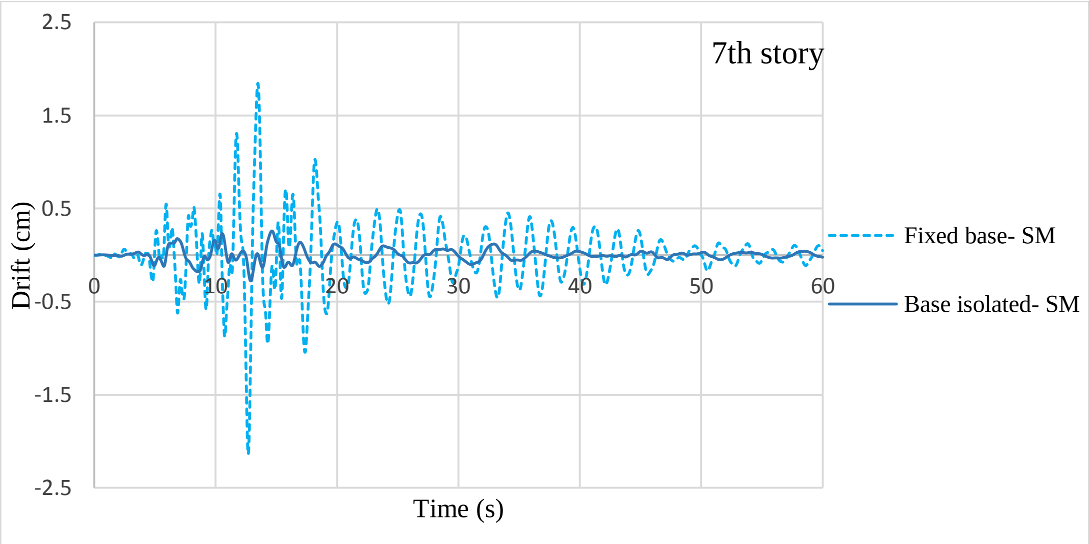
d)


5th story
2.5
1.5
0.5
-0.5
-1.5
-2.5
Drift (cm)
0
10
20
30
40
50
60
Time (s)
Fixed base- SM
Base isolated- SM

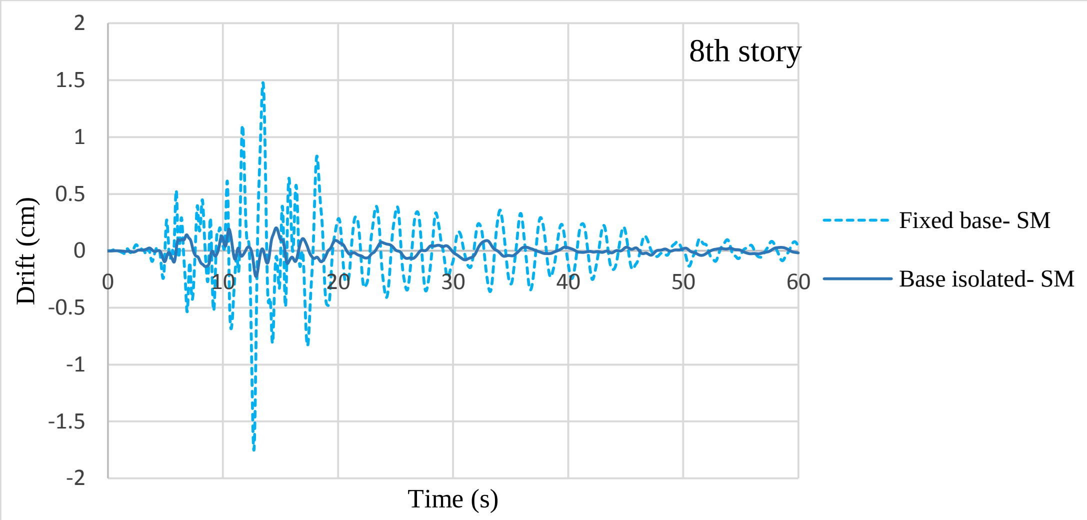
e)


6th story
2.5
1.5
0.5
-0.5
-1.5
-2.5
Drift (cm)
0
10
20
30
40
50
60
Time (s)
Fixed base- SM
Base isolated- SM

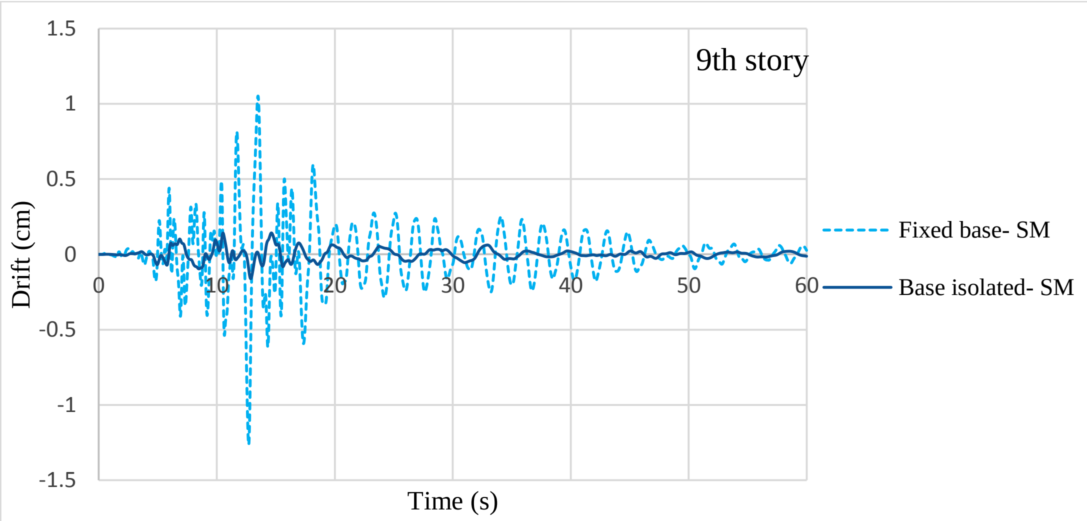
f)


7th story
2.5
1.5
0.5
-0.5
-1.5
-2.5
Drift (cm)
0
10
20
30
40
50
60
Time (s)
Fixed base- SM
Base isolated- SM

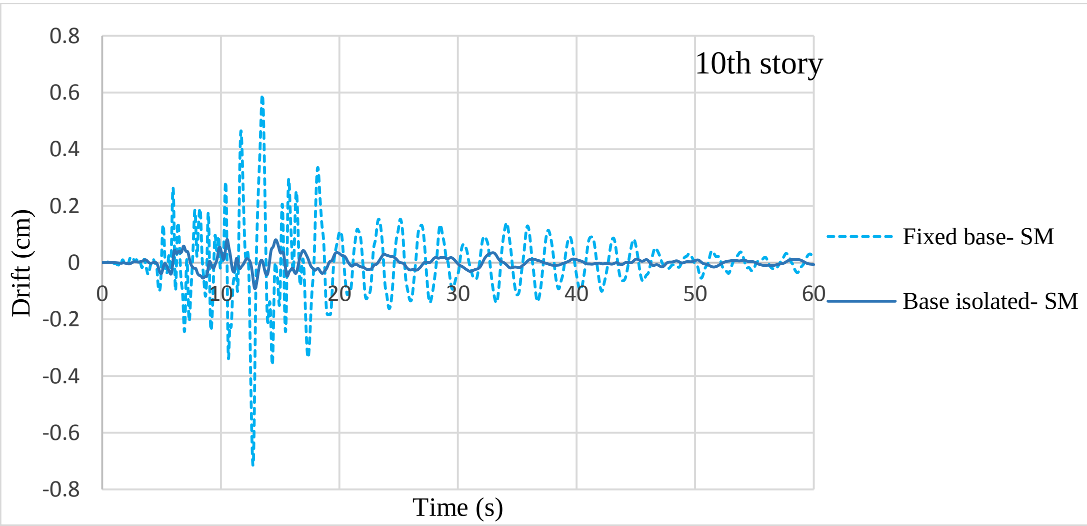
g)



h)



i)



j)

Figure 4.24 Story drift – time history plot of 10 story model under Santa Monica earthquake

4.3 Analysis results of 15-story buildings

It is a natural that increasing the number of stories of the building leads to increase the loads on the bearing of the structure. It has been observed that increasing the number of stories to 15-story, led to rise the load on the one bearing up to 600 kN, also the time period was increased in the nonlinear time history analysis to 3.59 s when increasing the story number to 15-story of the building with the fixed base. While the parameters of lead rubber base isolation of the effective stiffness and the initial stiffness decreased up to 208 kN/m and 175 kN/m respectively.

4.3.1 Corralitos (C) earthquake loaded on 15-story building

When loading the Corralitos seismic force as a dynamic load on a model of 15-story the fixed base case did not change significantly the value of the relative displacement at the roof of the building about the previous case with 10-story model. The reason for this is due to the effect of the building design and the response of building with characteristics of earthquake motion. Moreover, the utilization of base isolation led to reducing the relative displacement up to 3.73 cm at the fifteenth level, while the relative displacement in fixed base building up to 21.57 cm, as shown in Figure 4.25. Furthermore, the inter-story drift with the story height is considered a good index to the safety of the building, it indicates to the stresses on the elements of the building due to the impact of the earthquake. If it has a small value, the building was safer and less deformation at the earthquake occurred. The results of the analysis in Figure 4.26 showed that the use of base isolation led to a decrease in the value of drift ratio, which has a maximum value up to 0.22%, while the maximum inter-story drift ratio in the fixed base building up to 0.66%.

In addition to that, the relationship for the relative displacement between the roof and bearing of the building with time is given in Figure 4.27. It was shown that the advantage of base isolation in damping of earthquake acceleration and reducing the response of the building by decreasing its motion. Also, the drift with time in Figure 4.28 for all stories were displayed, and showed the effects of base isolation in the control of the building vibration by the damping of the earthquake, and reducing the rebound movement of the building. That is required to maintain the building and equipment safely against the impact of different earthquake motions.

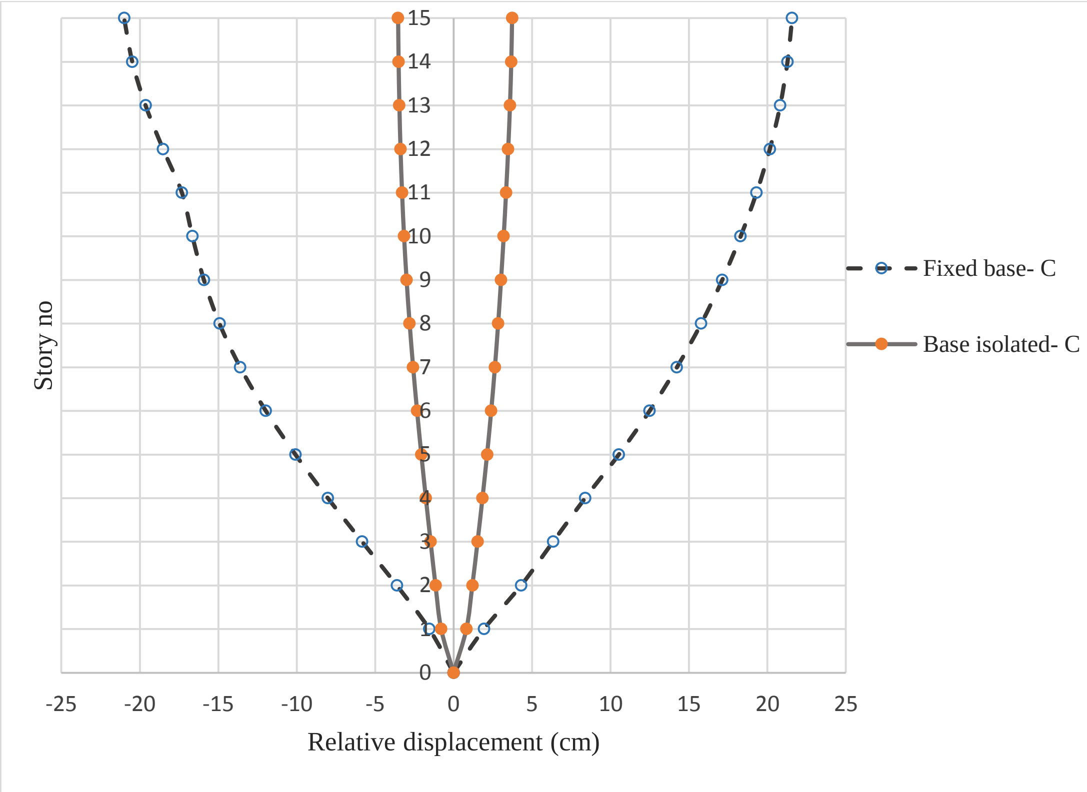


Figure 4.25 Relative displacement for 15 story model with fixed base and base isolation under Corralitos earthquake

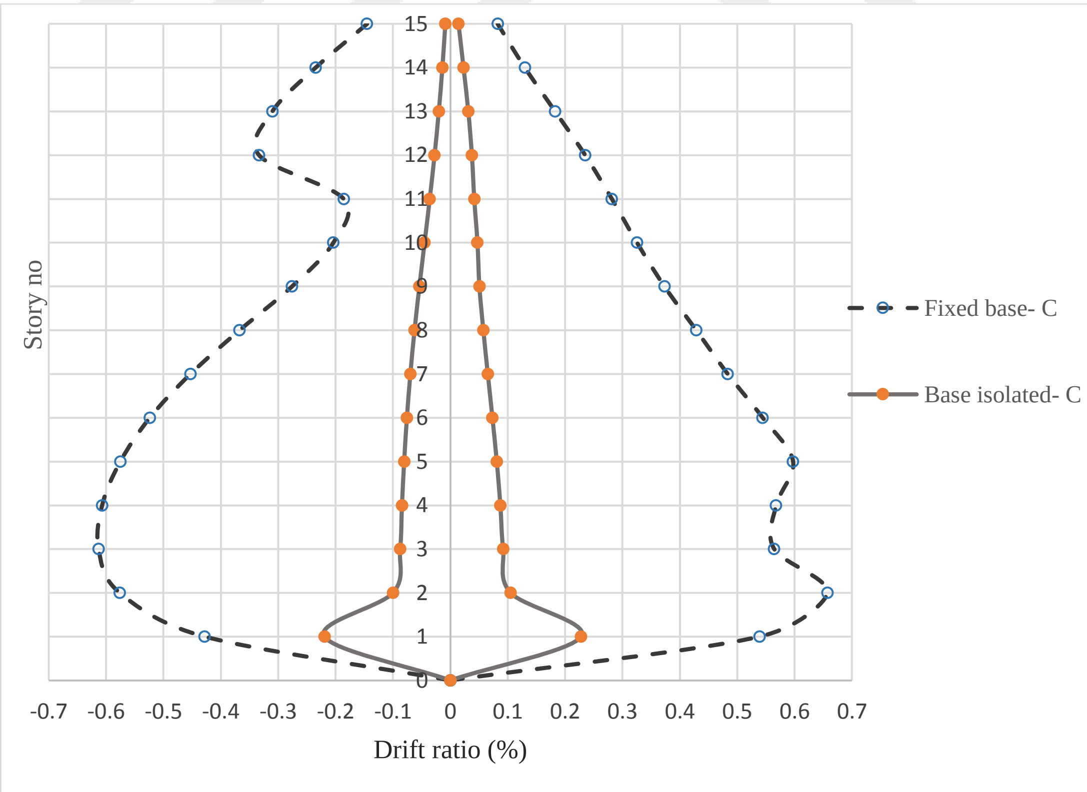


Figure 4.26 Drift ratio for 15 story model with fixed base and base isolation under Corralitos earthquake

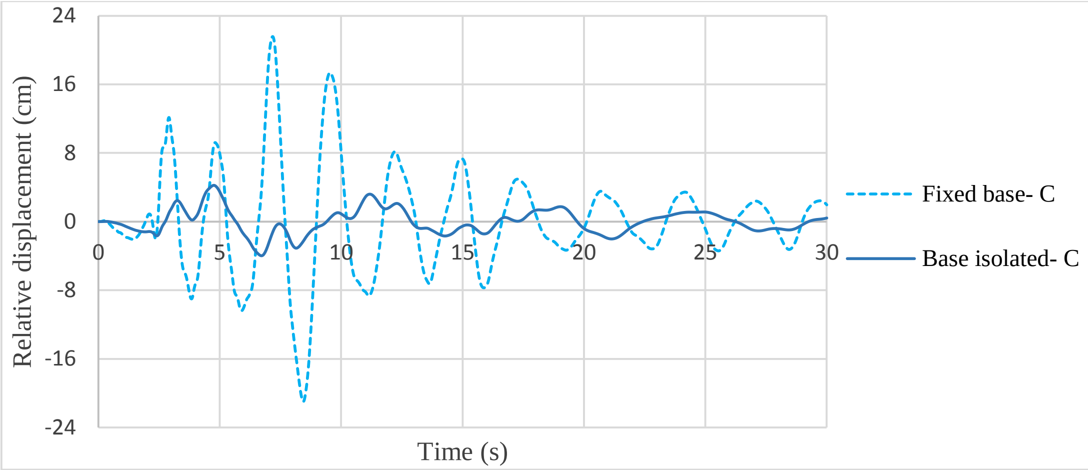
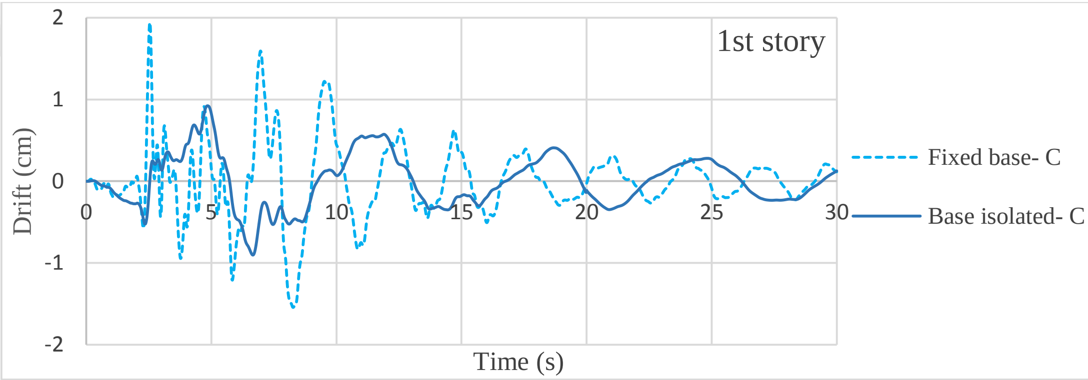
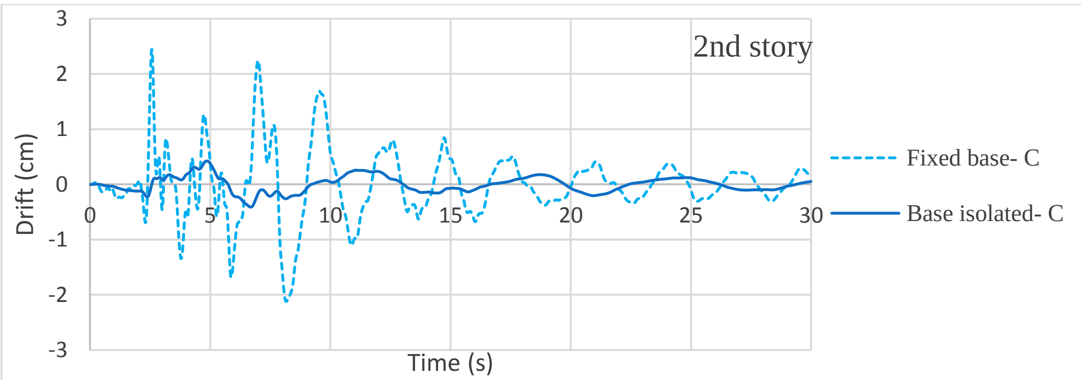


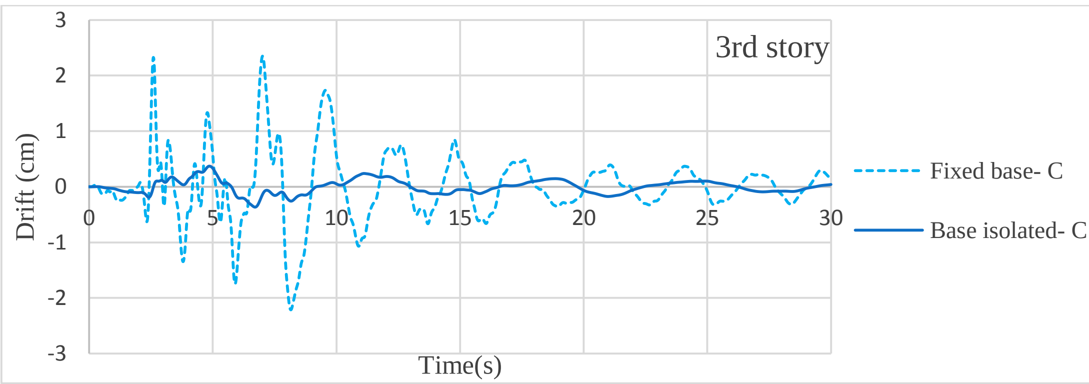
Figure 4.27 Relative roof displacement – time history plot of 15-storey model under Corralitos earthquake



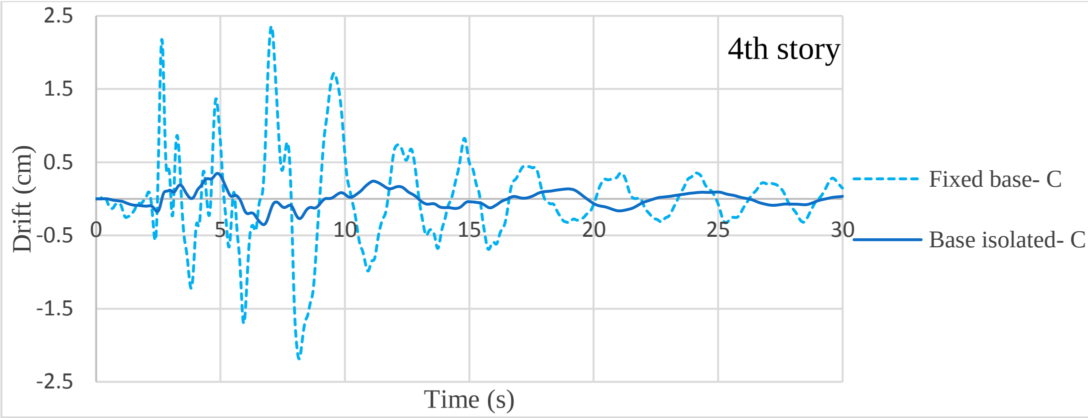
a)



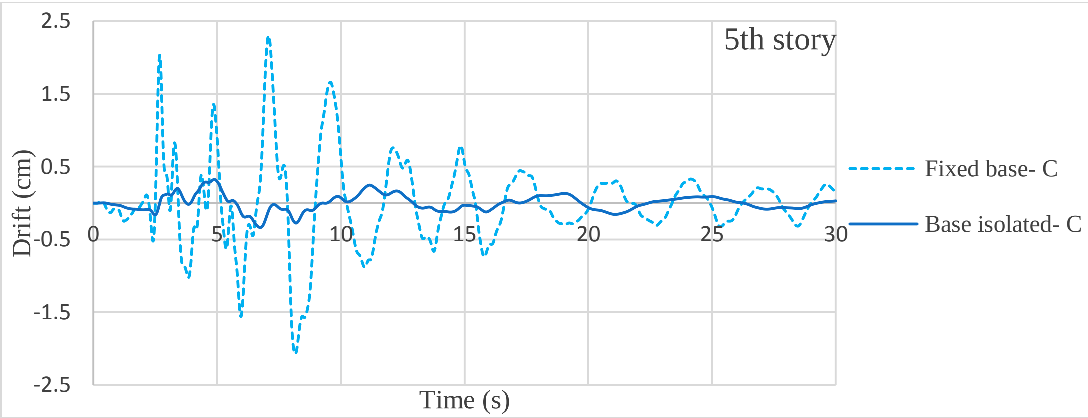
b)



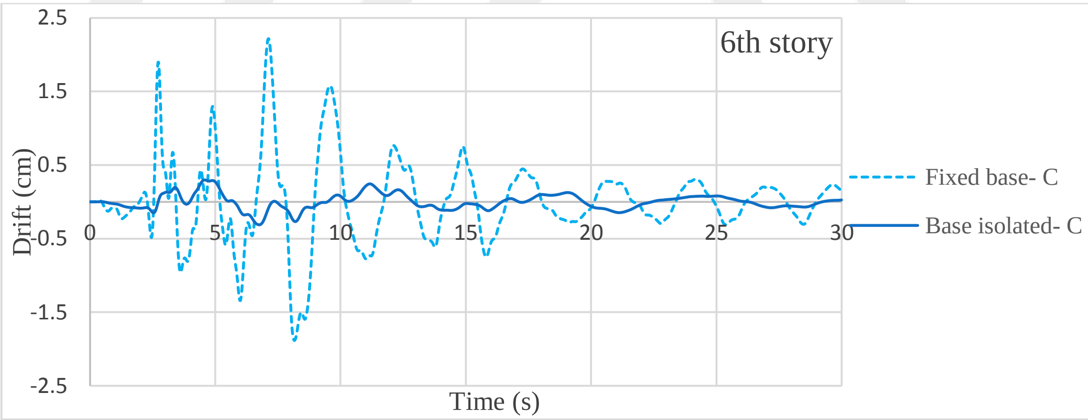
c)


4th story
Drift (cm)
Time (s)
Fixed base- C
Base isolated- C
2.5
1.5
0.5
-0.5
-1.5
-2.5
0
5
10
15
20
25
30

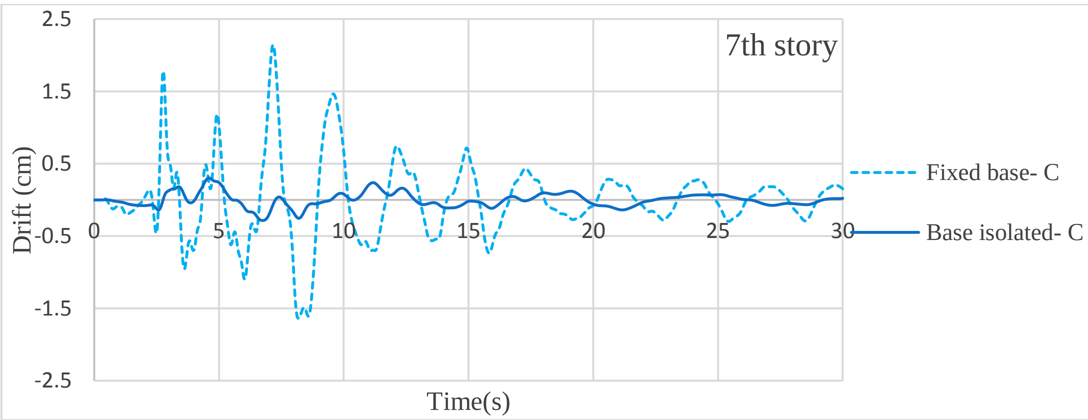
d)


5th story
Drift (cm)
Time (s)
Fixed base- C
Base isolated- C
2.5
1.5
0.5
-0.5
-1.5
-2.5
0
5
10
15
20
25
30

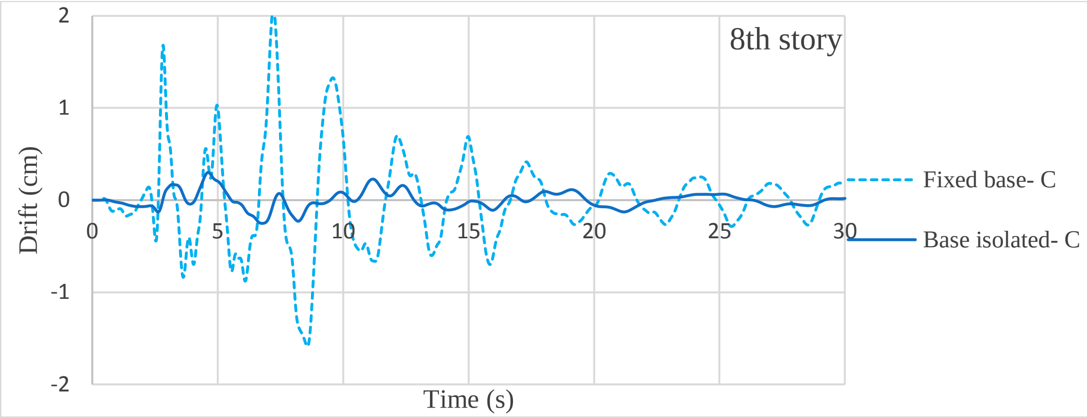
e)


6th story
Drift (cm)
Time (s)
Fixed base- C
Base isolated- C
2.5
1.5
0.5
-0.5
-1.5
-2.5
0
5
10
15
20
25
30

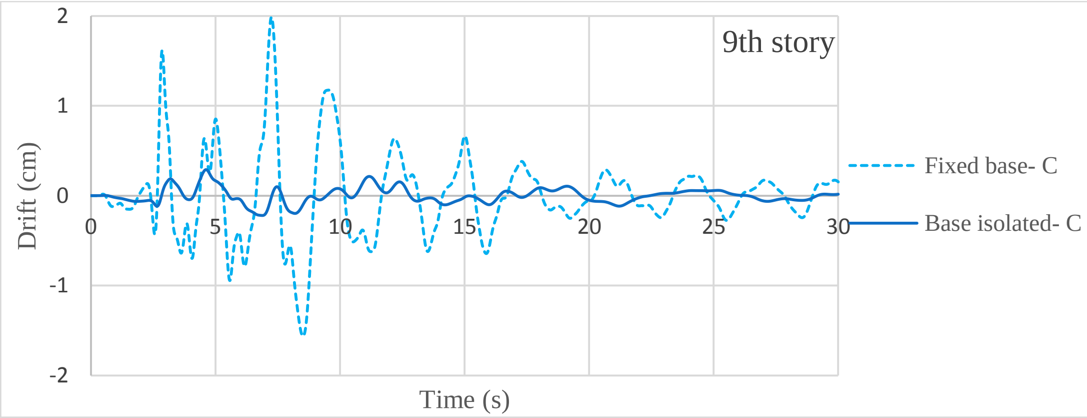
f)


7th story
Drift (cm)
Time(s)
Fixed base- C
Base isolated- C
2.5
1.5
0.5
-0.5
-1.5
-2.5
0
5
10
15
20
25
30

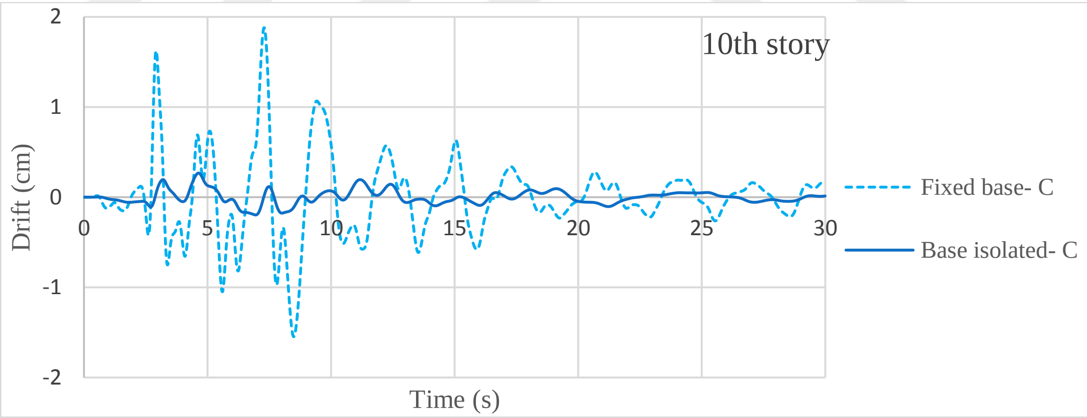
g)


8th story
Drift (cm)
Time (s)
Fixed base- C
Base isolated- C

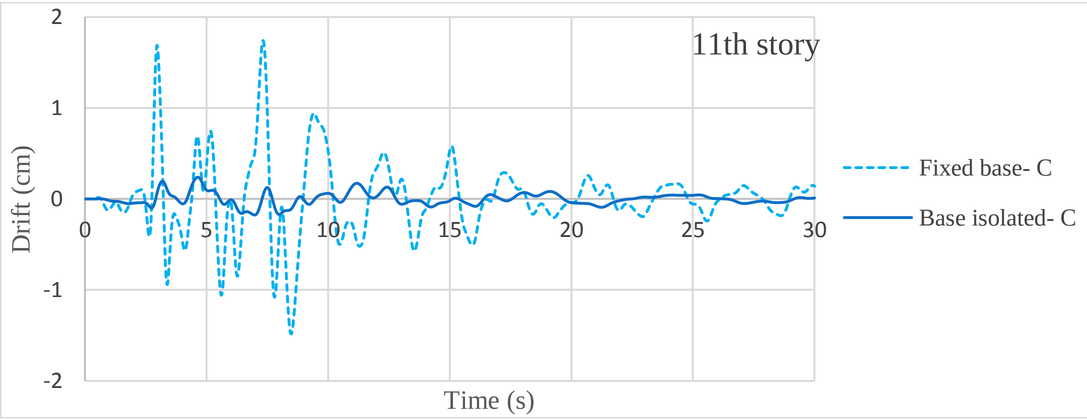
h)


9th story
Drift (cm)
Time (s)
Fixed base- C
Base isolated- C

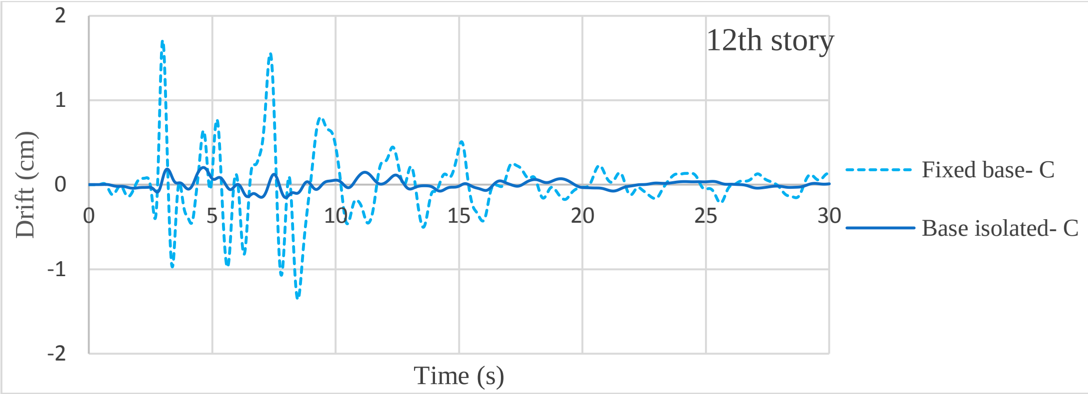
i)


10th story
Drift (cm)
Time (s)
Fixed base- C
Base isolated- C

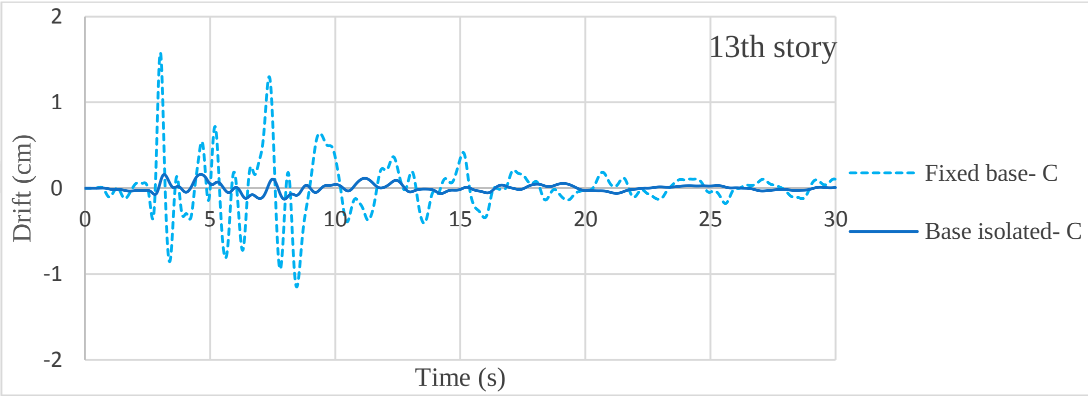
j)


11th story
Drift (cm)
Time (s)
Fixed base- C
Base isolated- C

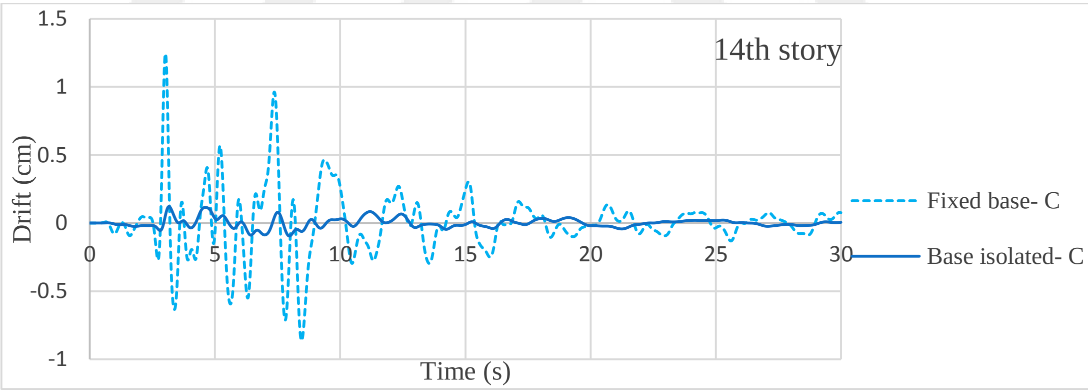
k)



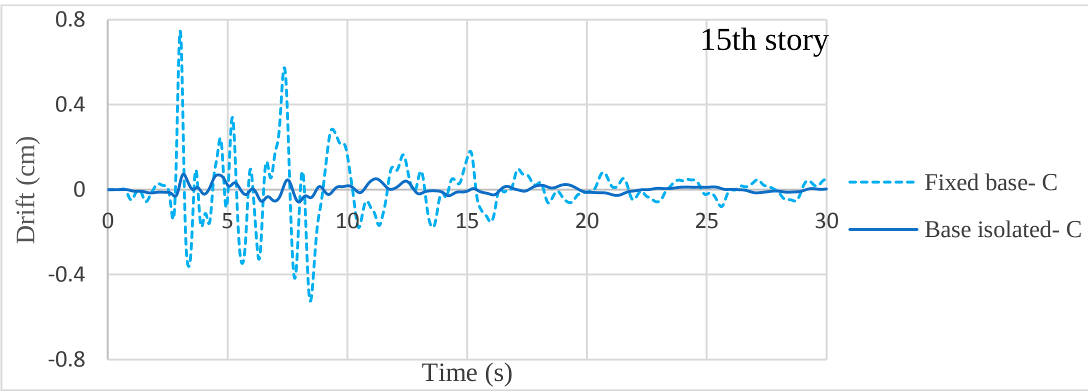
l)



m)



n)



o)

Figure 4.28 Story drift – time history plot of 15 story model under Corralitos earthquake

4.3.2 Northridge (N) earthquake loaded on 15-story building

The Northridge earthquake is classified as one of the strongest earthquakes which was happening in the United States in 1994. Its strength is evident in the recoil speed of the acceleration wave of the earthquake. In this study the impact of this earthquake affected the building response with a fixed base that made the amount of relative displacement on the top floor up to 19.5 cm, while this value (relative displacement between top-story and bearing level) has been reduced to 2.7 cm when using the base isolation system. This is evident in Figure 4.29. Also, the results of plotting the relationship between the inter-story drift ratio and the height of the building are delineated in Figure 4.30. It is noted that the curve of the building with fixed base is non-smooth (curvy) due to the acceleration caused by the earthquake. The highest value of the drift ratio in this case was up to 0.48%, while the curve of the building with the isolated base was a smooth and the values had been decreased where the maximum value of the inter-story drift ratio up to 0.17%. This clearly shows the effect of the use of the base isolation system in reducing the inter-story drift ratio of building elements, which reduces the stresses and increase the safety factor in the building.

In addition to this, the relative displacement between the top story and bearing level with time of the earthquake is shown in Figure 4.31. It is noted that the effect of the base isolation system in decreasing the displacement of the building is remarkable and the movement of the structure by reducing the impact of the acceleration of the earthquake on the building was clear due to the installation of isolation device. Moreover, the variation of drift with time at all stories of the 15 story building is given in Figure 4.32. Similar to the previous figures mentioned, with the base isolation, the drift significantly decreases in the structures in comparison to the fixed base case. It is also noted that the difference becomes more pronounced at the upper stories. This makes construction more stable against the impact of the earthquakes motion.

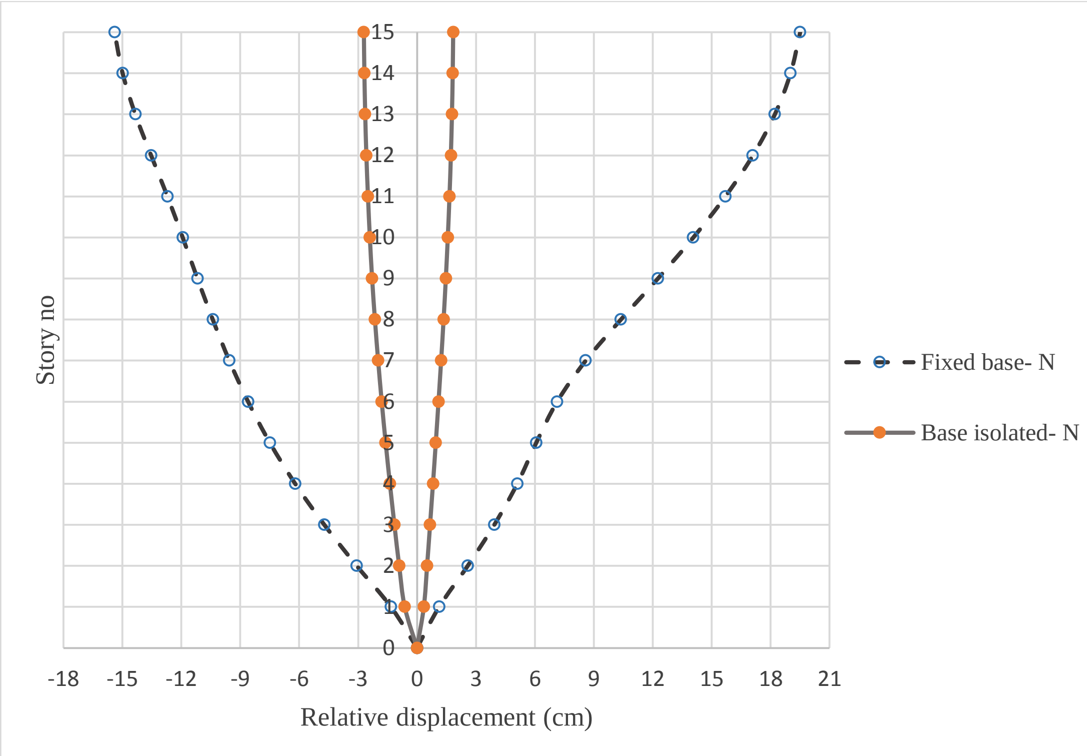


Figure 4.29 Relative displacement for 15 story model with fixed base and base isolation under Northridge earthquake

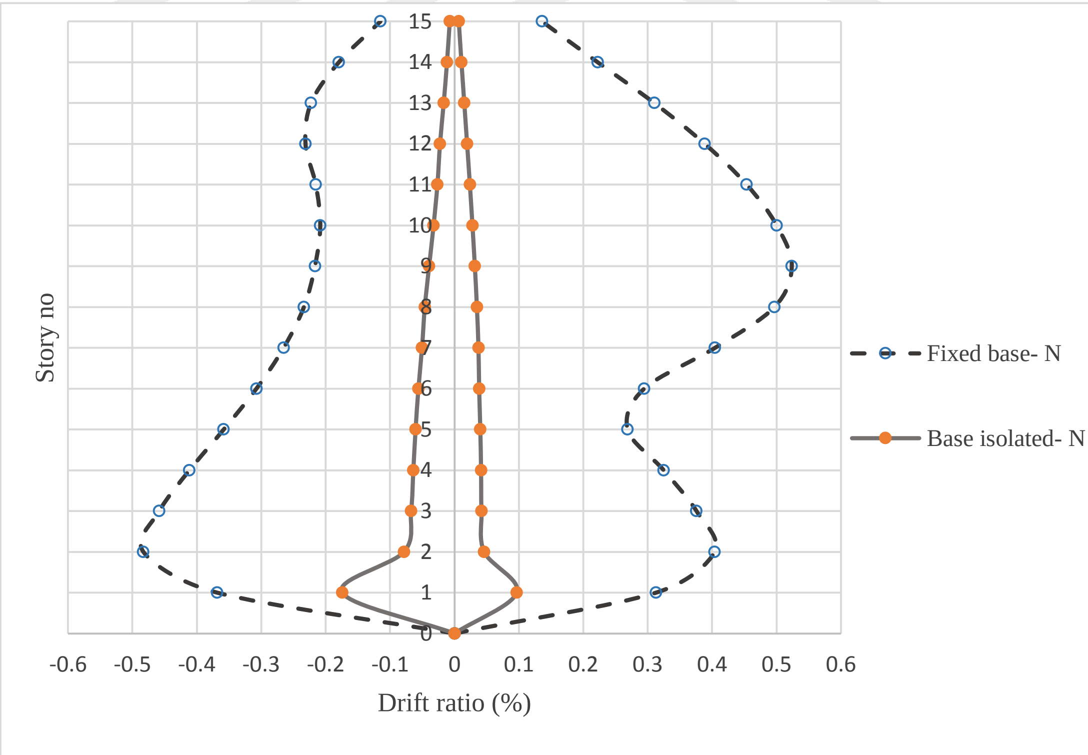


Figure 4.30 Drift ratio for 15 story model with fixed base and base isolation under Northridge earthquake

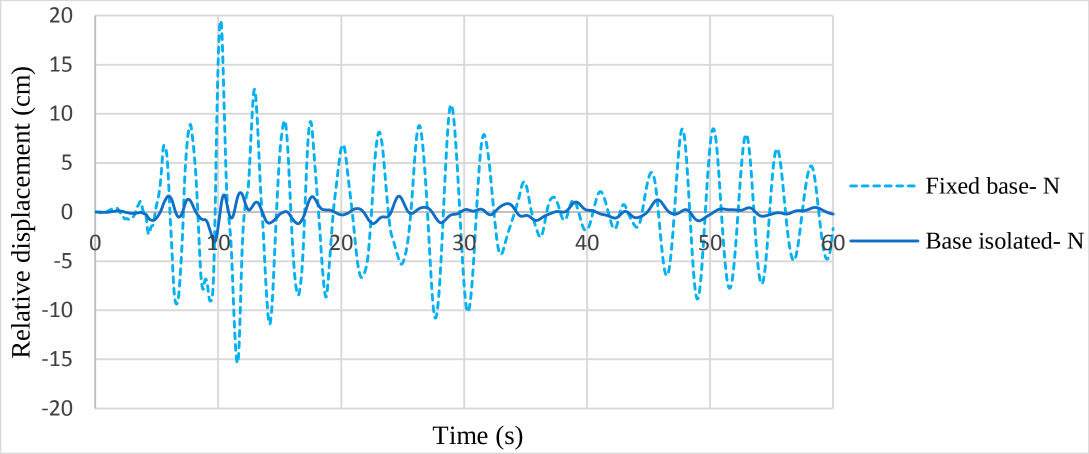
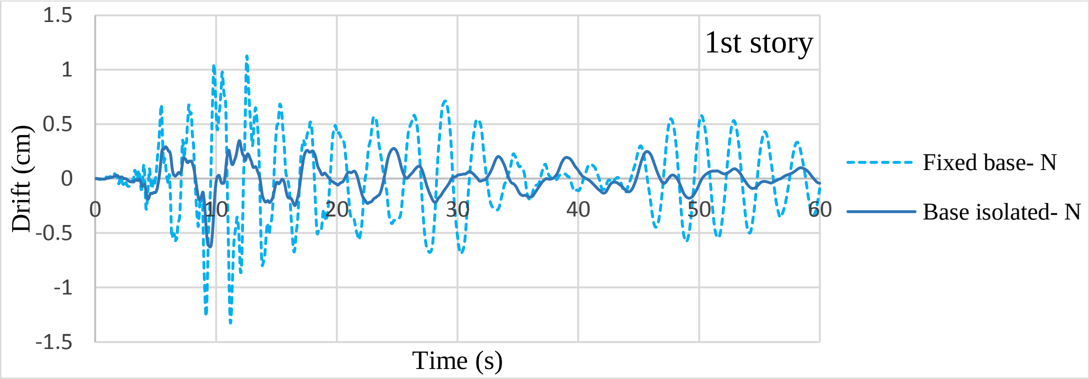
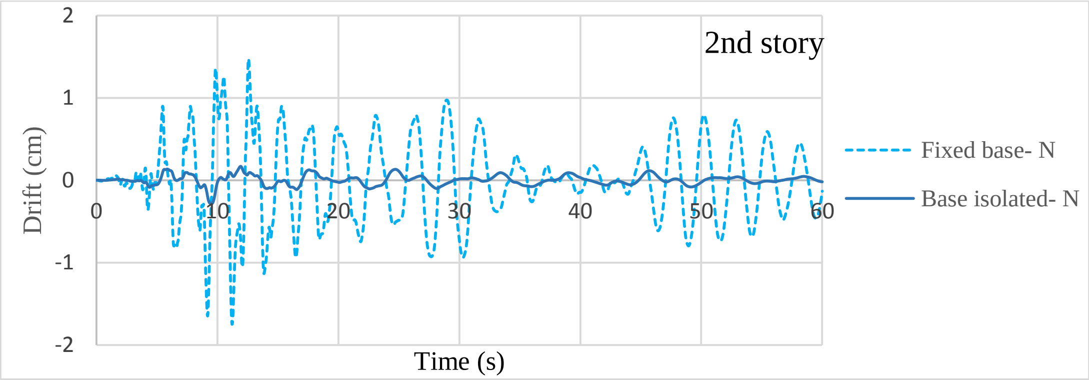


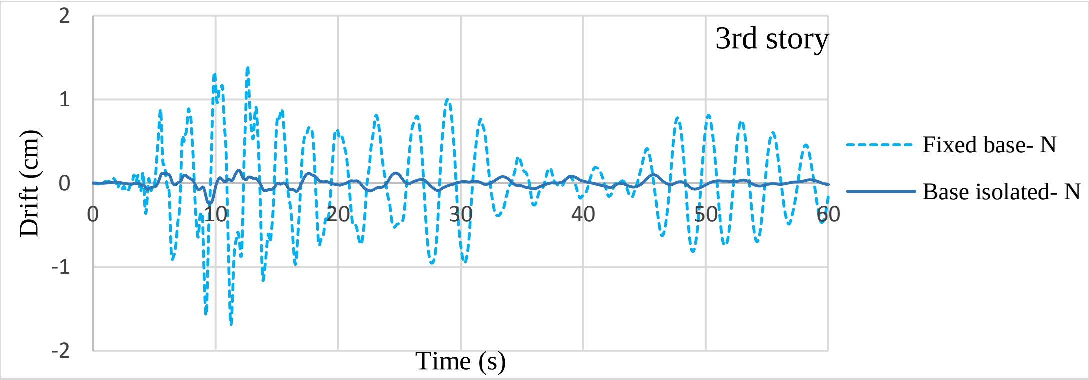
Figure 4.31 Relative roof displacement – time history plot of 15 story model under Northridge earthquake



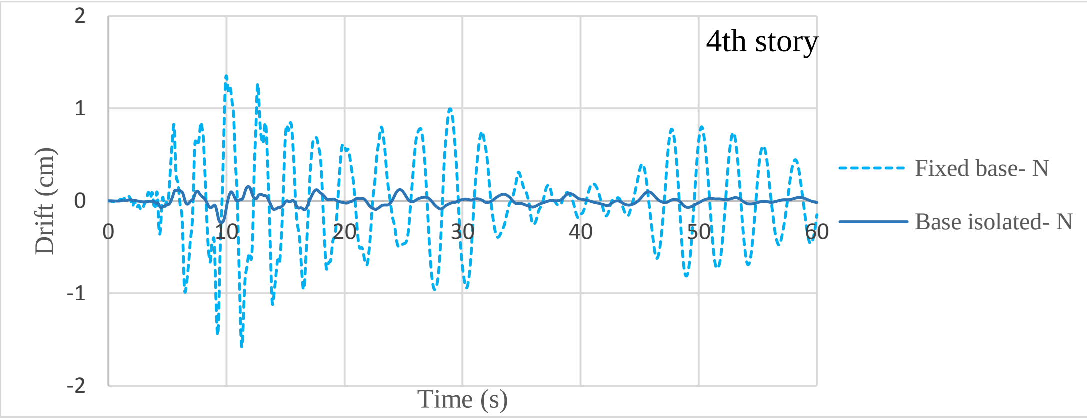
a)



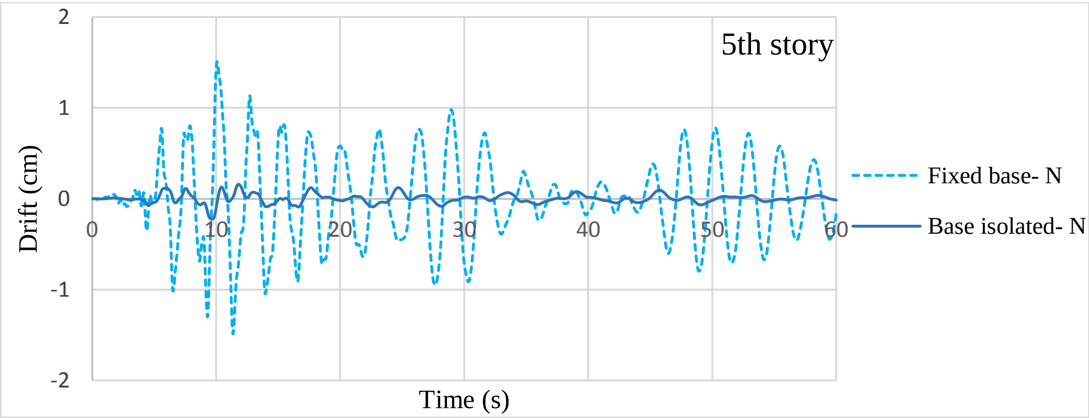
b)



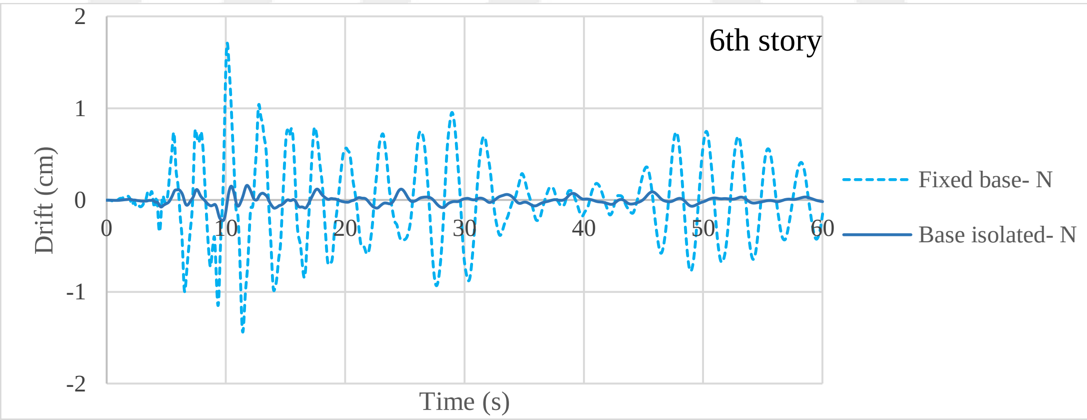
c)


4th story
Drift (cm)
Time (s)
Fixed base- N
Base isolated- N

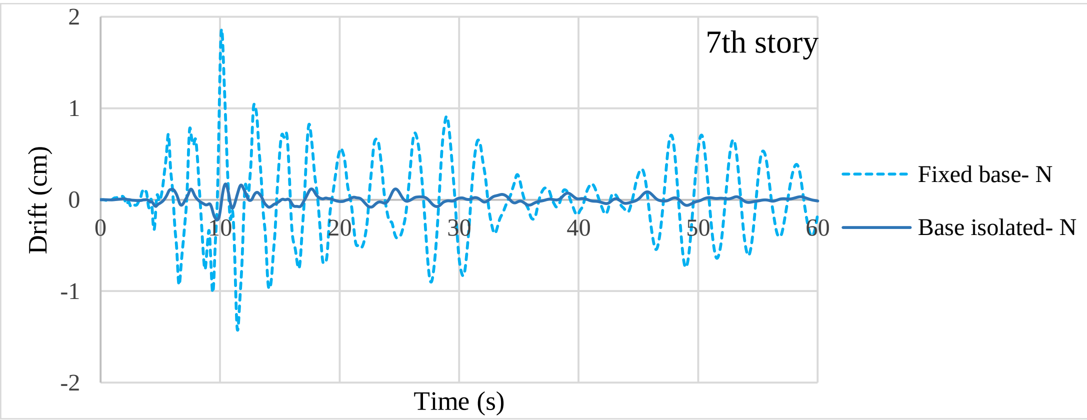
d)


5th story
Drift (cm)
Time (s)
Fixed base- N
Base isolated- N

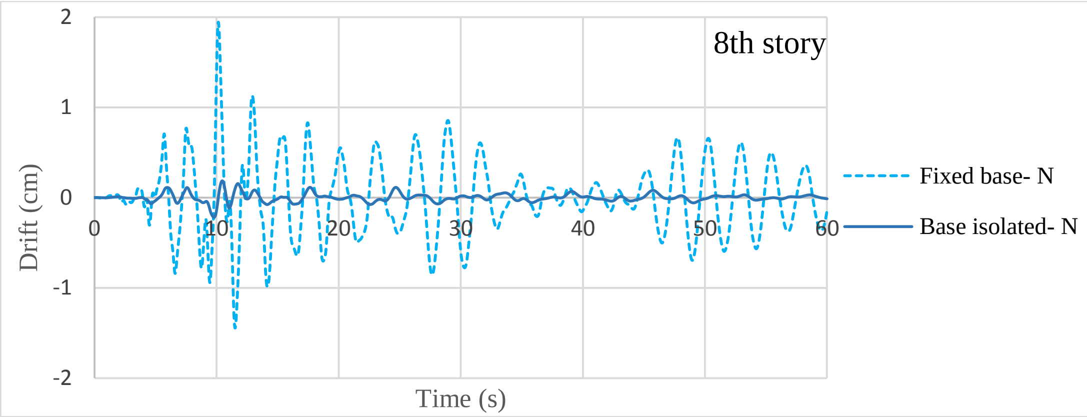
e)


6th story
Drift (cm)
Time (s)
Fixed base- N
Base isolated- N

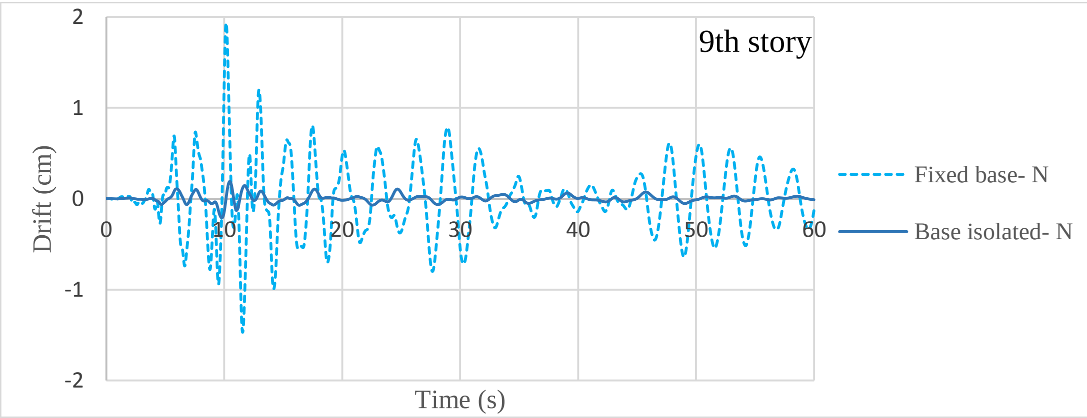
f)


7th story
Drift (cm)
Time (s)
Fixed base- N
Base isolated- N

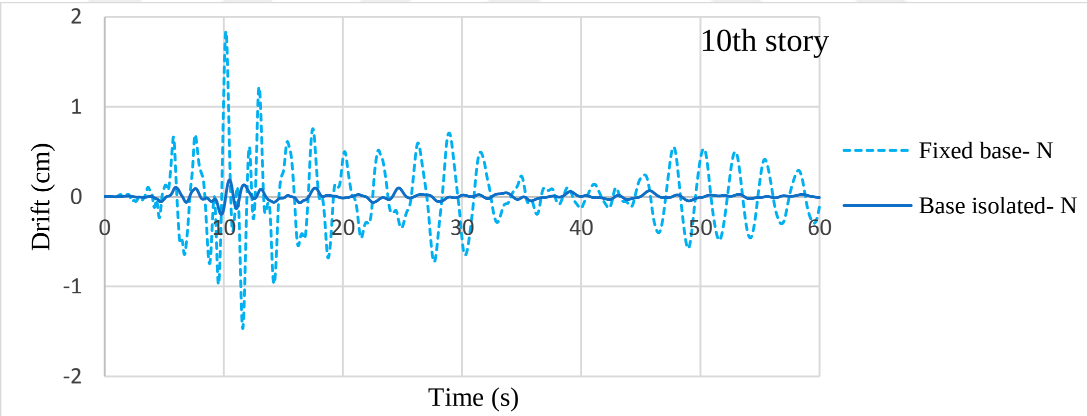
g)


8th story
Drift (cm)
Time (s)
Fixed base- N
Base isolated- N

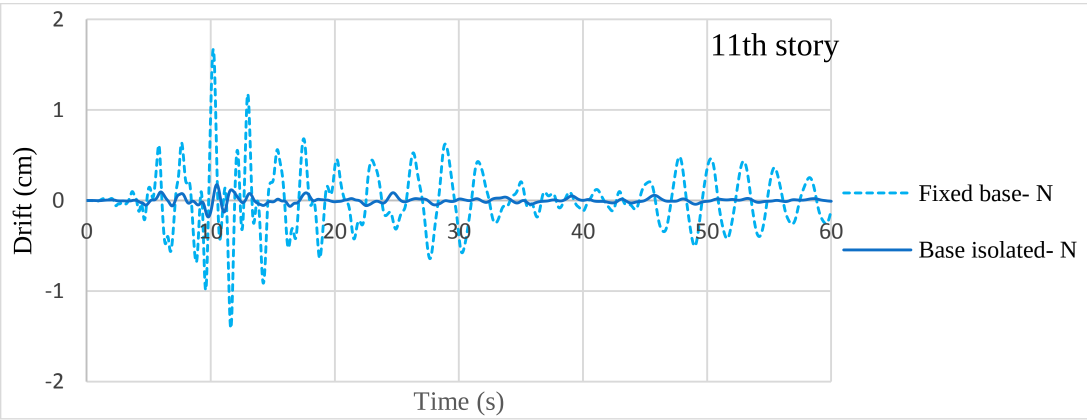
h)


9th story
Drift (cm)
Time (s)
Fixed base- N
Base isolated- N

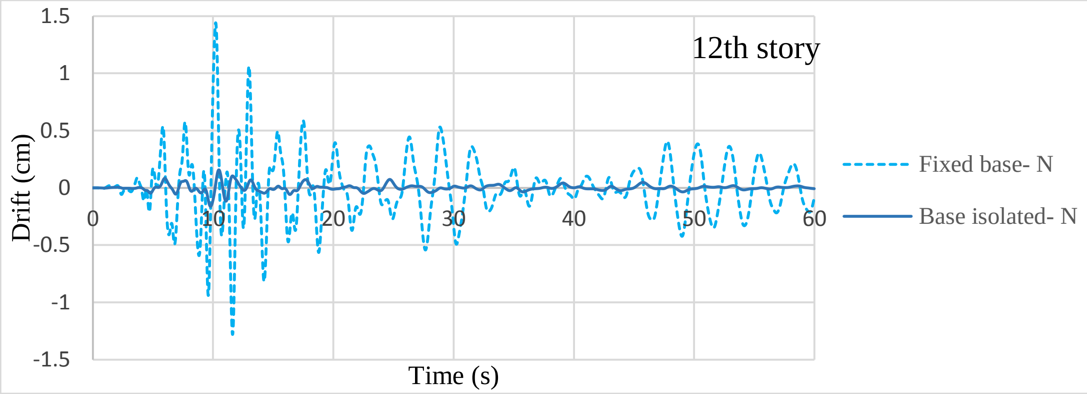
i)


10th story
Drift (cm)
Time (s)
Fixed base- N
Base isolated- N

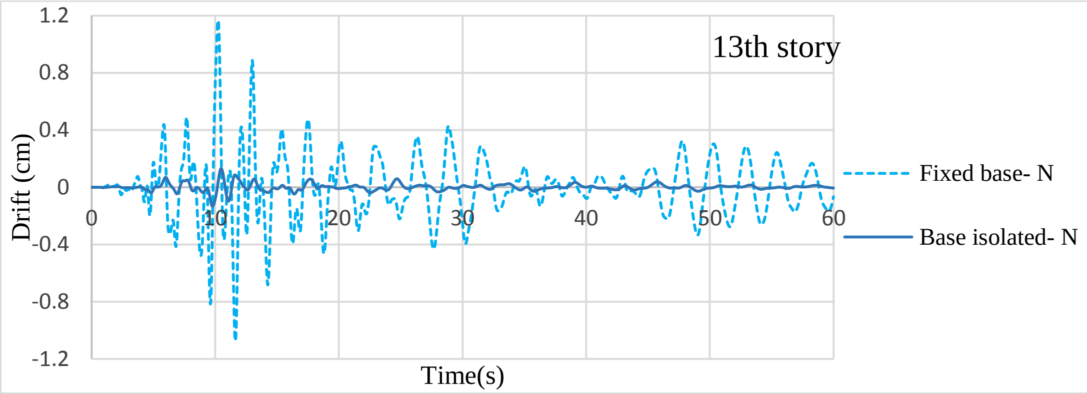
j)


11th story
Drift (cm)
Time (s)
Fixed base- N
Base isolated- N

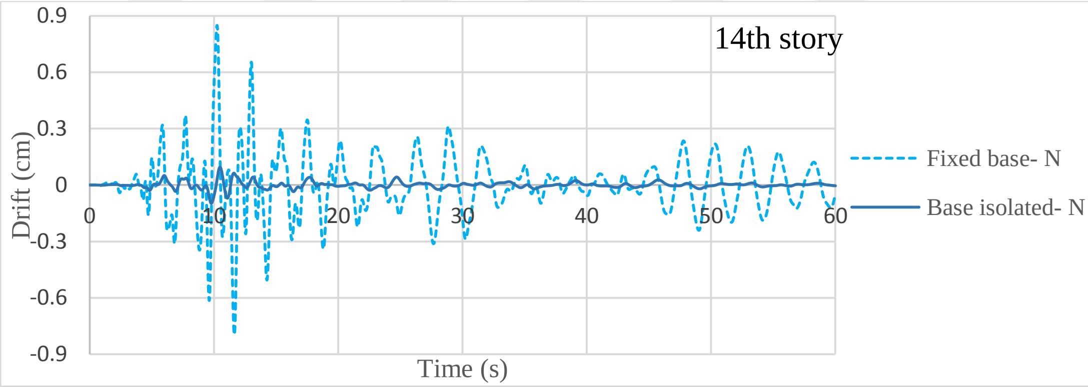
k)



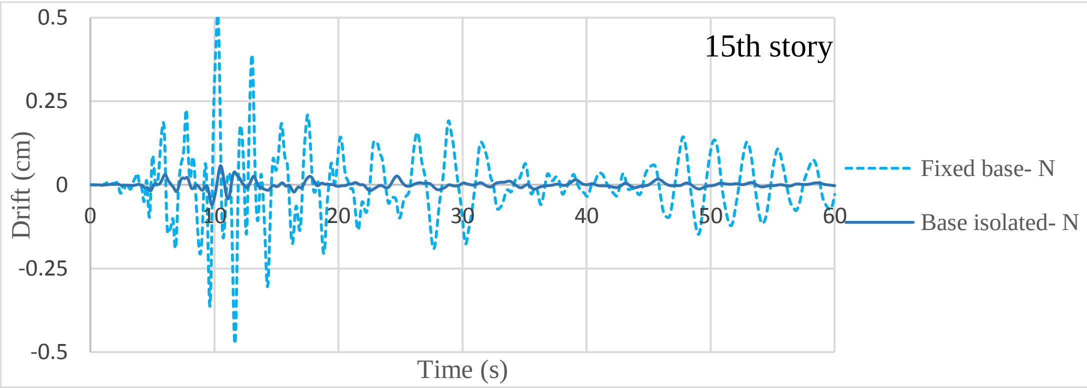
l)



m)



n)



o)

Figure 4.32 Story drift– time history plot of 15 story model under Northridge earthquake

4.3.3 Santa Monica (SM) earthquake loaded on 15-storey building

The effect of Santa Monica earthquake on the 15-story model was larger than two previous earthquakes studied. When compared to the three models, the effect of Santa Monica earthquake on the 10-story model and the 15-story were the most influential, while in the 5-story model was the least influential, that's because the building's response to the earthquake depends on the properties of the building in terms of area and height, as well as the materials types of the building elements, and the response of the structure to seismic acceleration. The relative displacement at the top of the building was a value up to 32.45 cm for the building with fixed base while it has been decreased to 2.3 cm at the same level when the base isolation system has been used in the building as delineated in Figure 4.33. Furthermore, the impact of the earthquake on the inter-story drift ratio to story height was also greater compared with the other two earthquakes (Corralitos and Northridge) for the building had 15-storey with a fixed base. It was found that the maximum inter-story drift ratio value of the fixed-base building was up to 0.85%. It has been decreased by using the base isolation system to 0.19% as a maximum. This clearly indicates the effectiveness of the base isolation system in reducing the drift ratio by giving flexibility to the building to move horizontally, while maintaining its vertical position when the earthquake motion occurs as illustrated in Figure 4.34.

On the other hand, when studying the movement of the building under the influence of the earthquake with time as show in Figure 4.35, the effect of using the rubber base isolation to reduce the relative displacement between the top story and the base level under the impact of the time of the earthquake was greater. Moreover, the response of the building was controlled and reduced the stresses on the elements of the building due to the isolation. Also, the results given in Figure 4.36 indicate that the drift with time at all stories has been decreased by using the base isolation system in comparison to the fixed base case. In addition, it is indicating to the ability of the base isolation to dampening the movement of the structure by giving some flexibility in the horizontal movement in order to absorb the kinetic energy of the earthquake and reduce the acceleration of the movement of the building under the influence of the earthquake motion. that gives the construction of safer and more stable against the movement caused by earthquakes.

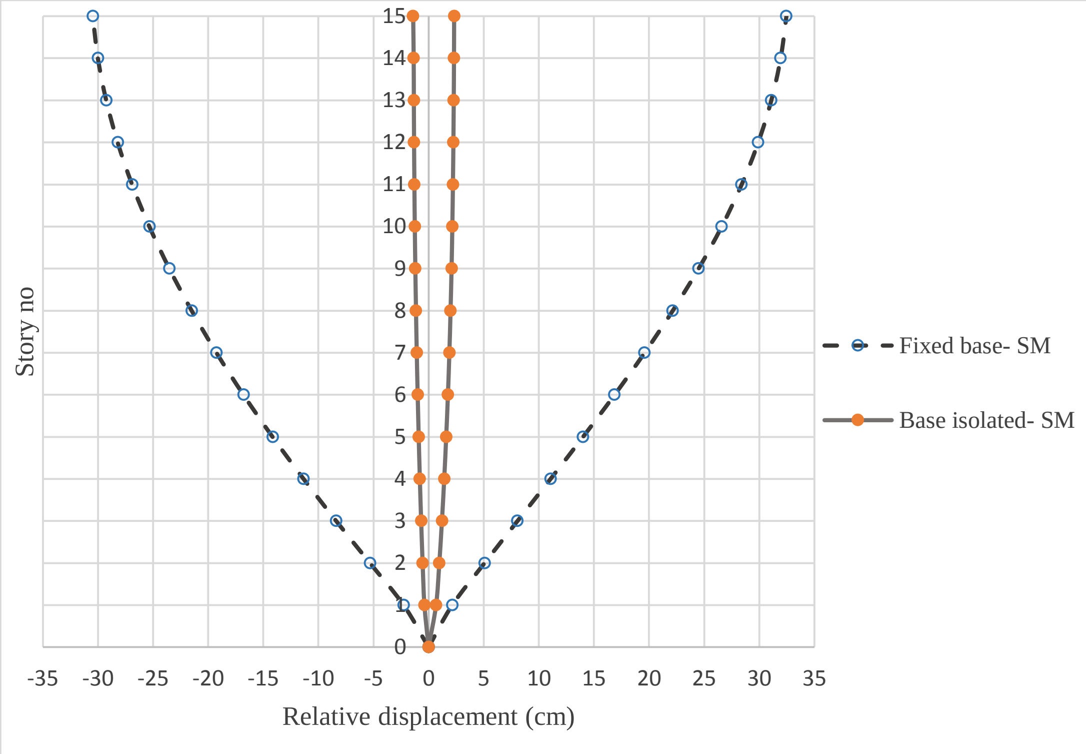


Figure 4.33 Relative displacement for 15 story model with fixed base and base isolation under Santa Monica earthquake

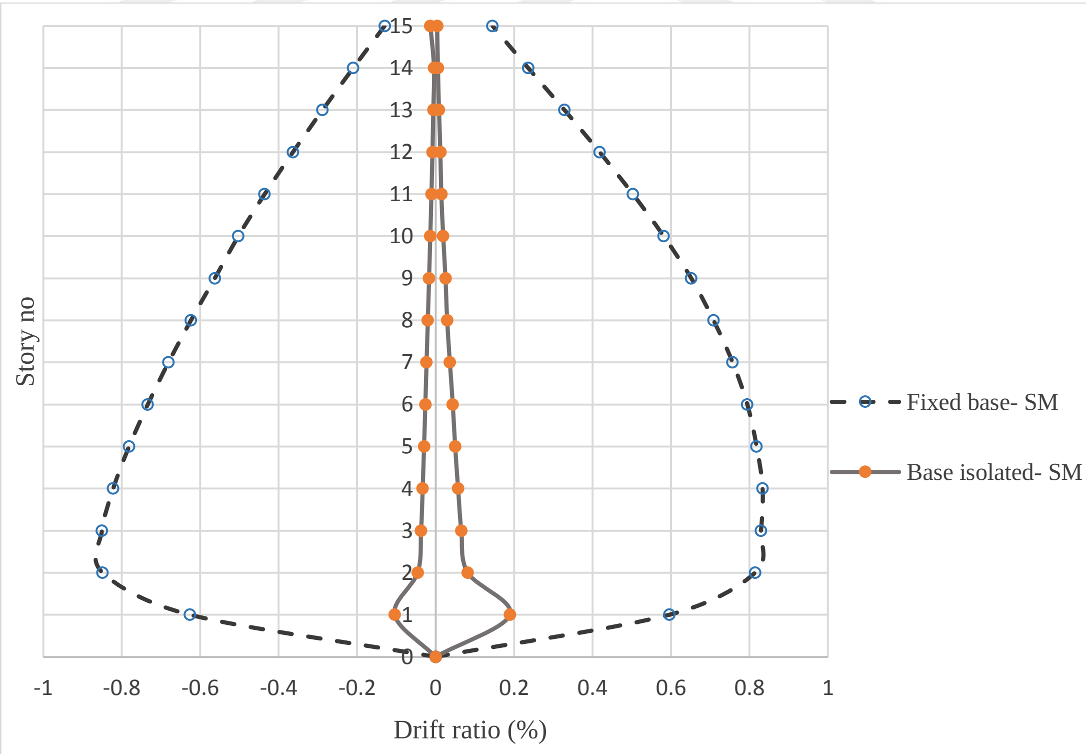


Figure 4.34 Drift ratio for 15 story model with fixed base and base isolation under Santa Monica earthquake

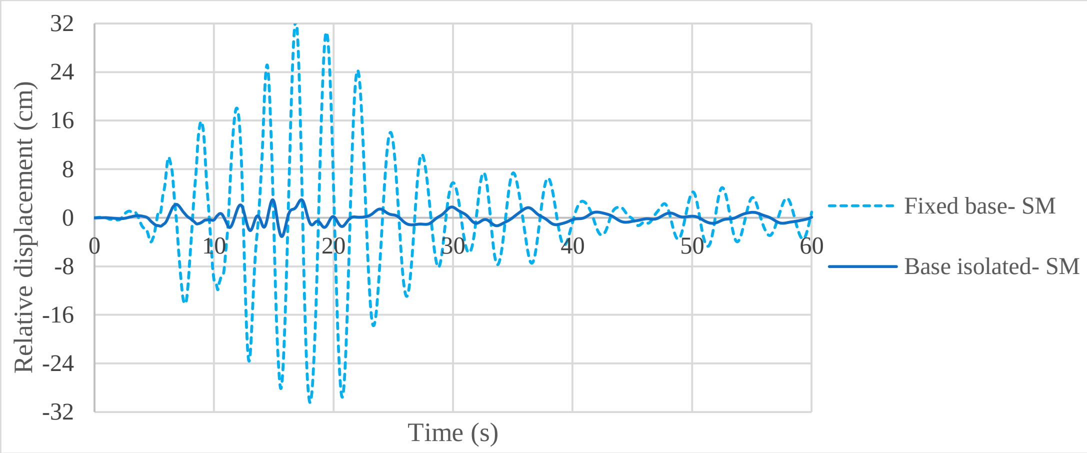
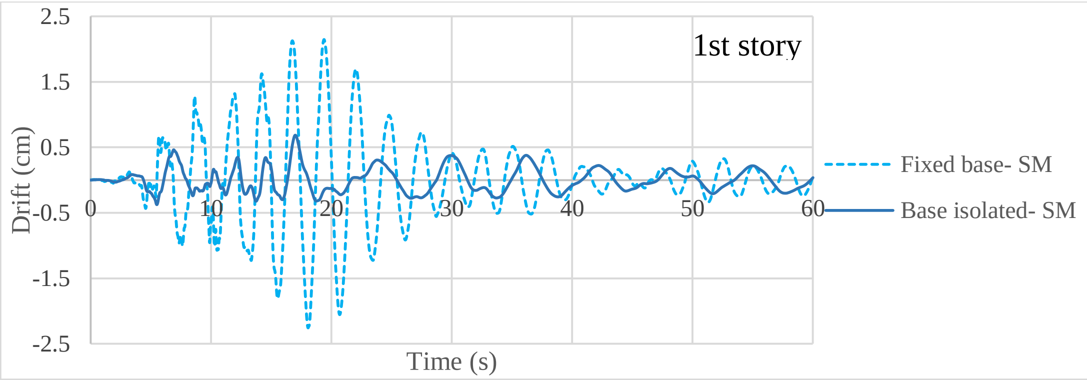
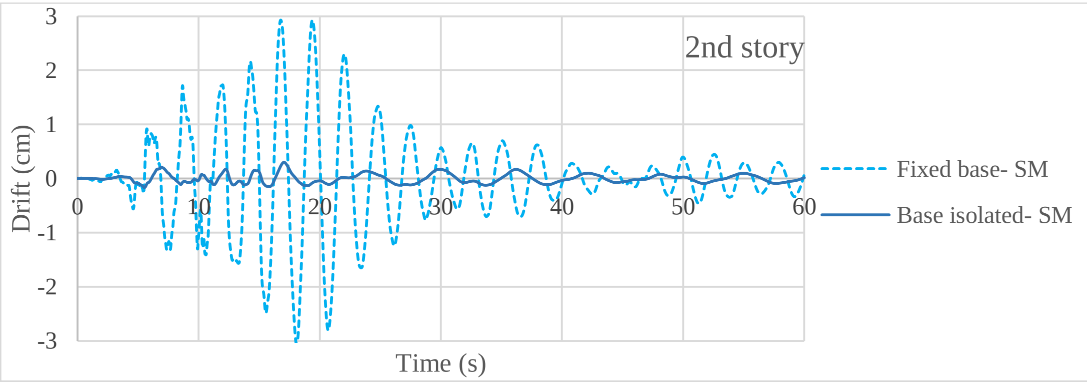


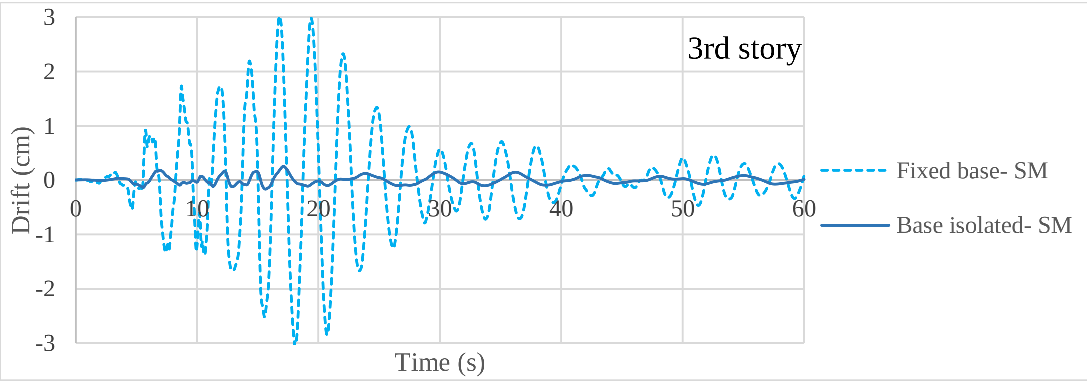
Figure 4.35 Relative roof displacement – time history plot of 15 story model under Santa Monica earthquake



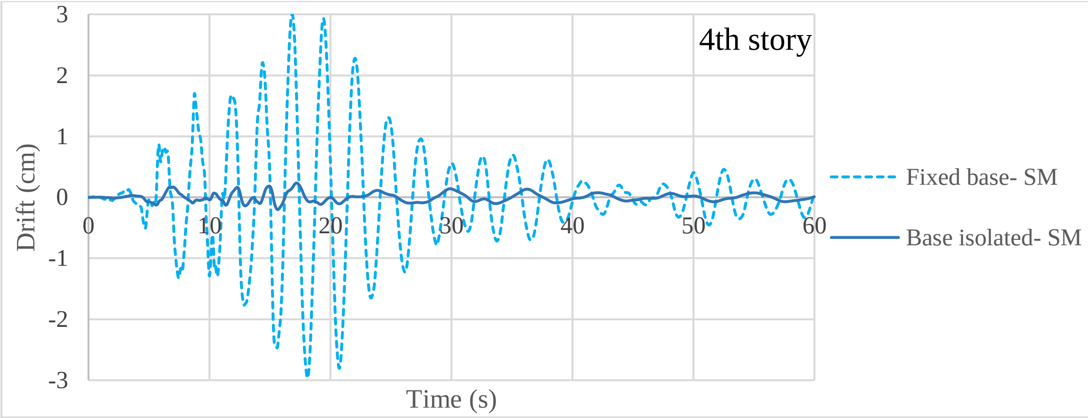
a)



b)

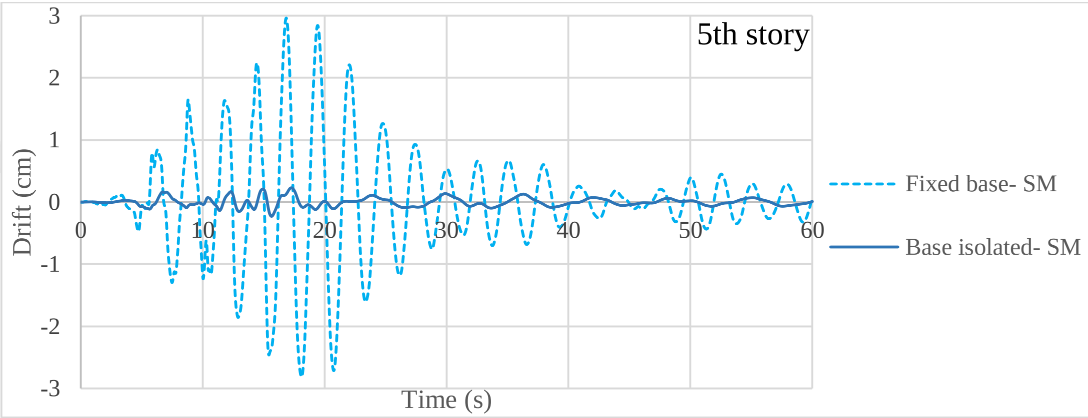


c)



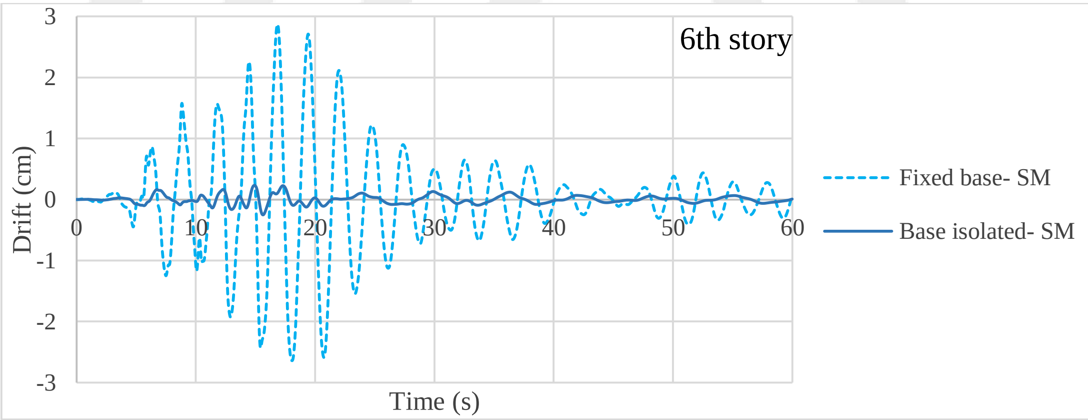
4th story
Drift (cm)
Time (s)
Fixed base- SM
Base isolated- SM

d)



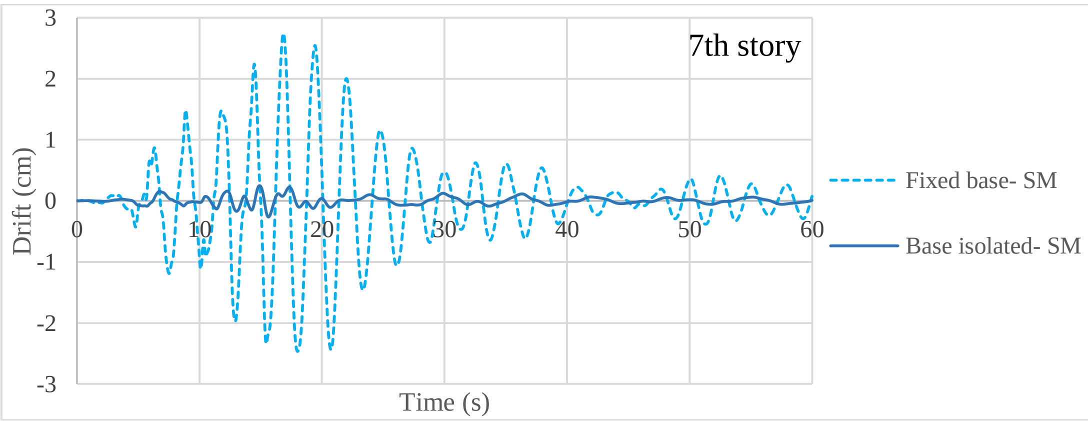
5th story
Drift (cm)
Time (s)
Fixed base- SM
Base isolated- SM

e)



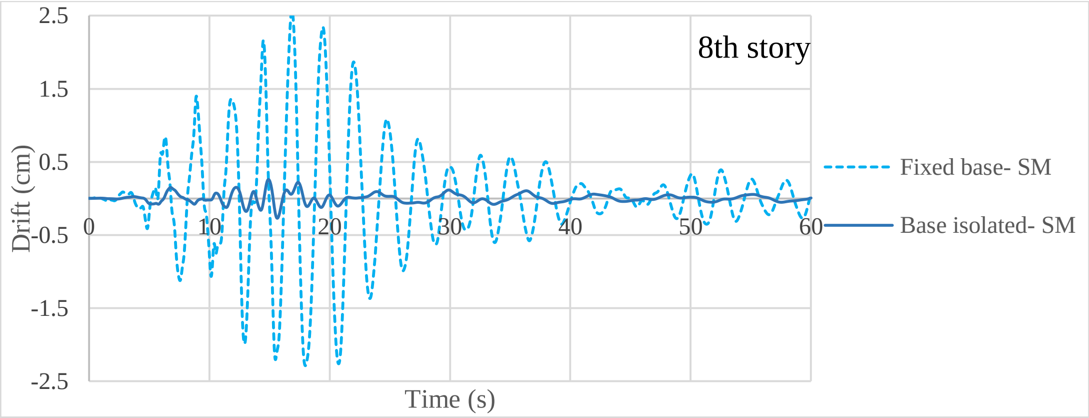
6th story
Drift (cm)
Time (s)
Fixed base- SM
Base isolated- SM

f)

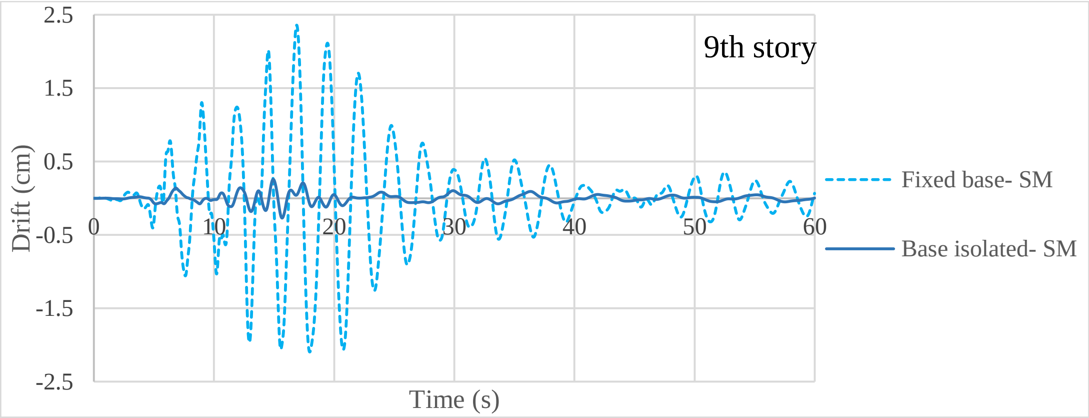


7th story
Drift (cm)
Time (s)
Fixed base- SM
Base isolated- SM

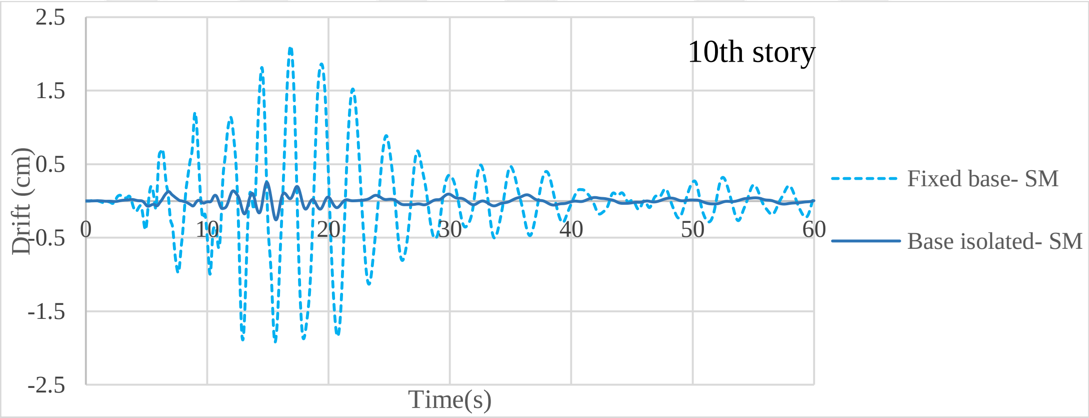
g)


8th story
2.5
1.5
0.5
-0.5
-1.5
-2.5
Drift (cm)
0
10
20
30
40
50
60
Time (s)
Fixed base- SM
Base isolated- SM

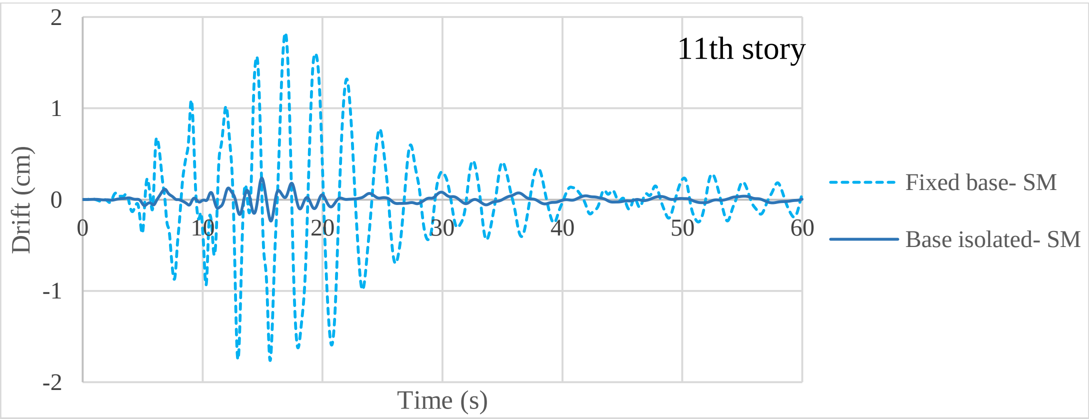
h)


9th story
2.5
1.5
0.5
-0.5
-1.5
-2.5
Drift (cm)
0
10
20
30
40
50
60
Time (s)
Fixed base- SM
Base isolated- SM

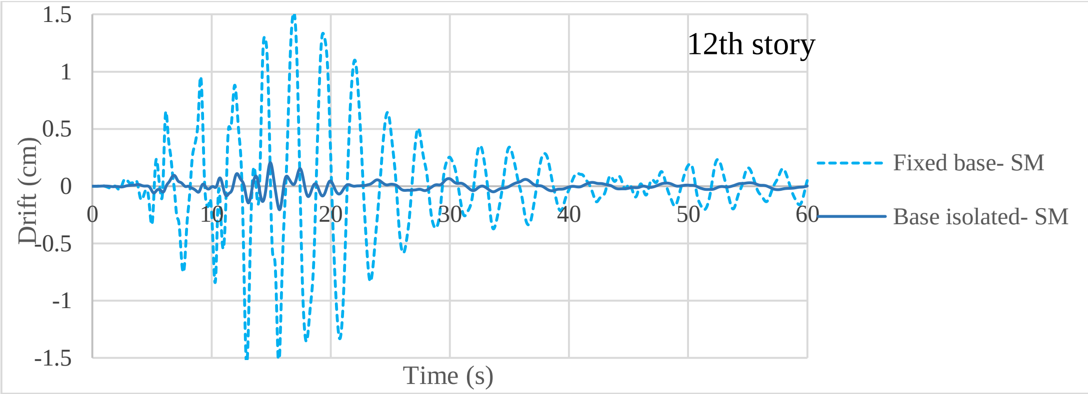
i)


10th story
2.5
1.5
0.5
-0.5
-1.5
-2.5
Drift (cm)
0
10
20
30
40
50
60
Time(s)
Fixed base- SM
Base isolated- SM

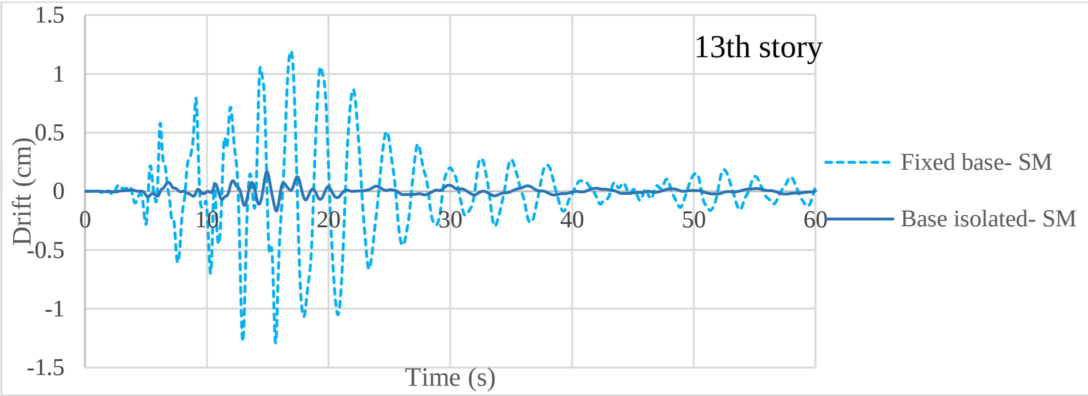
j)


11th story
2
1
0
-1
-2
Drift (cm)
0
10
20
30
40
50
60
Time (s)
Fixed base- SM
Base isolated- SM

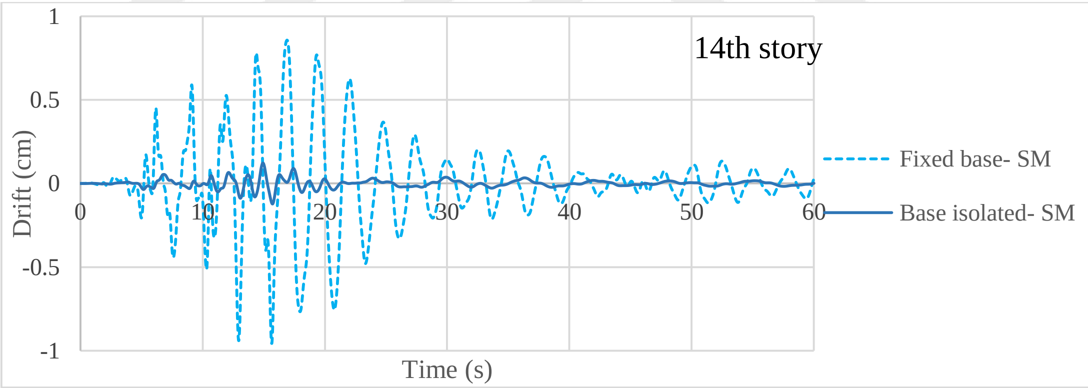
k)



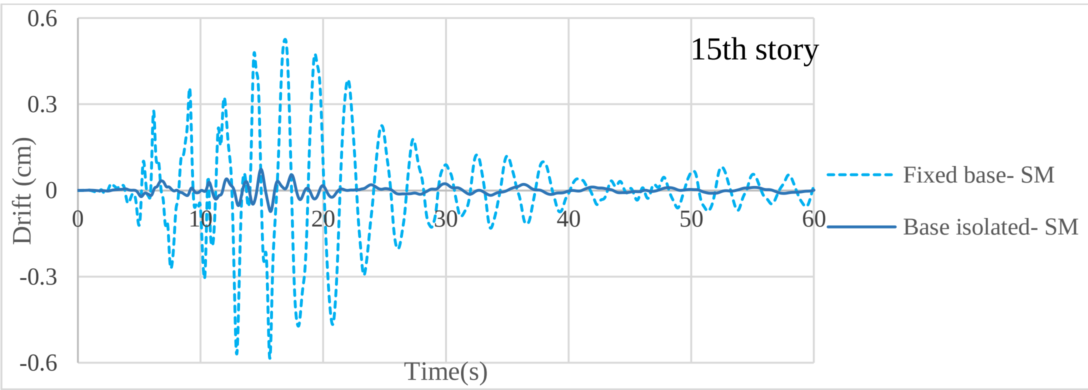
l)



m)



n)



o)

Figure 4.36 Story drift – time history plot of 15 story model under Santa Monica earthquake

CHAPTER 5

CONCLUSIONS

In this study, the effects of the base isolation system, which is formed from lead core rubber bearing isolators on the seismic response of the 5, 10, and 15 story steel frame buildings were investigated. This has been done by applying nonlinear time history analysis under three earthquake accelerations. The objectives are to advance the understanding of the behavior of the building with base isolation and building with fixed base under the effects of different earthquakes, and a comparison between both cases in the alteration in the response of the buildings in terms of the maximum relative displacement with the number of story, maximum inter-story drift, story drift variation with time, and relative displacement between top story and bearing of building with time. The following conclusions are drawn from this study:

- The relative displacement at the roof of the building decreased to 4.2, 6.0 and 8.4 times for the 5, 10 and 15 story buildings, respectively by using of the base isolation system. It could be noted that the base isolation was more effective when the height of the building was increased. Generally, it was reduced the stresses on the elements of the building as compared to the building with a fixed base.
- The analysis of the results indicated that the effect of using the base isolation system in reducing the maximum drift ratio for the building were up to 2.2, 2.5, and 3.8 times for the 5, 10, and 15 story frame structures, respectively. Furthermore, it gave some flexibility to the building to move horizontally during the ground motion, with maintaining the building in a vertical position. This made the building more safety and keeps the equipment from damage due to the earthquakes motion.
- The relationship between the relative displacement between the roof and the bearing of the building with a time of the earthquake revealed the effectiveness of the base isolation system in limiting the building's response to the seismic motion by damping the movement of the building, and reduced the intensity of the vibration of the structure.

- When studying the behavior of the building for each story under the influence of the earthquake by drawing the relationship between the story drift variation with time for both cases (structure with base isolated and with fixed base). It was clear the effect of the base isolated in reducing the drift and damping the movement of the building, especially on the upper stories. In addition to reducing the acceleration of the building that occurs as a result of the acceleration of the earthquake, this reduced the risk to the building due to the seismic forces and gives greater durability to the building.
- It could be also noted that with the change in the design parameters and properties of the base isolation system, the required level of seismic response would be achieved for the buildings. The base isolation systems worked to dissipate the energy caused by the earthquake to increase the level of damping in the building to reduce displacements to acceptable levels.

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