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M.Sc. in Civil Engineering

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UNIVERSITY OF GAZİANTEP

GRADUATE SCHOOL OF

NATURAL & APPLIED SCIENCES

USE OF FRICTION PENDULUM ISOLATOR TO IMPROVE THE EARTHQUAKE RESPONSE OF STEEL BUILDING

M. Sc. THESIS

IN

CIVIL ENGINEERING

BY

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Supervisor

Assoc. Prof. Dr. Esra METE GÜNEYİSİ

by

Aws Wajeeh ABDULLAH

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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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Aws Wajeeh ABDULLAH

ABSTRACT

USE OF FRICTION PENDULUM ISOLATOR TO IMPROVE THE EARTHQUAKE RESPONSE OF STEEL BUILDING

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Base isolation systems have become a significant element of a structural system to enhance the reliability and safety of the structures during an earthquake. In this thesis, the earthquake behavior of a five story steel building with base isolation was investigated. To this aim, firstly the fixed base case of the structure was analyzed and then compared with the base isolated case. The building under consideration was rectangular in plan, measuring 30 m by 15 m with 5 m bays in both direction. The isolated building was assumed to be supported by friction pendulum system (FPS). The parametric study focused on different friction coefficients of seismic base isolators of FPS and its effect on the response of the structure. The modeling and dynamic analysis were done using finite element program. Three earthquake ground motion records were utilized. The analysis of the results showed a significant improvement in the dynamic response of the model structure after the application of the base isolation.

Keywords: Earthquake analysis, Friction coefficient, Friction pendulum system, Steel building, Seismic isolator.

ÖZET

ÇELİK BİR BİNANIN DEPREM DAVRANIŞININ İYİLEŞTİRİLMESİNDE SÜRTÜNMELİ SARKAÇ TİPİ İZOLATÖR KULLANIMI

ABDULLAH, AWS WAJEEH
Yüksek Lisans Tezi, İnşaat Mühendisliği Bölümü
Danışman: Doç. Dr. Esra METE GÜNEYİSİ
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96 sayfa

Taban izolasyon sistemleri, bir deprem esnasında yapıların güvenilirliğini ve emniyetini arttırmak için yapısal sistemin önemli bir unsuru haline gelmiştir. Bu tez çalışmasında, taban izolasyonlu beş katlı çelik bir binanın deprem davranışı incelenmiştir. Bu amaçla, öncelikle yapının ankastre mesnetli hali analiz edilmiş ve ardından taban izolasyonlu durumu ile karşılaştırılmıştır. Araştırmada kullanılan bina planda dikdörtgen ve her iki yönde 5 m'lik açıklıklı toplamda 30 x 15 m boyutlarındadır. İzole edilmiş binanın sürtünmeli sarkaç sistemi tarafından desteklendiği varsayılmıştır. Parametrik çalışma, sismik taban izolatörlerinin farklı sürtünme katsayılarına sahip olma durumlarını ve bunların yapının tepkisine etkisi üzerine odaklanmıştır. Modelleme ve dinamik analiz sonlu elemanlar programı kullanılarak yapılmıştır. Üç deprem yer hareketi kaydı kullanılmıştır. Sonuçların analizi, taban izolasyonunun uygulanmasından sonra model yapının dinamik tepkisinde belirgin bir iyileşme olduğunu göstermiştir.

Anahtar Kelimeler: Deprem analizi, Sürtünme katsayısı, Sürtünmeli sarkaç sistemi, Çelik yapı, Sismik izolatör.

To My Parents and My Wife

ACKNOWLEDGEMENT

All praise due to Allah, the Almighty, on whom ultimately we depend for sustenance and guidance. I am ever grateful to God, the Creator and the Guardian, and to whom I owe my very existence.

I would like to express my sincere thanks to my supervisor, Assoc. Prof. Dr. Esra METE GÜNEYİSİ, for all their help, patience, valuable advices, always providing and guiding me in the right direction. I’m very grateful and proudest to work under her academic guidance.

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LIST OF SYMBOLS/ABBREVIATIONS

μ	The Friction Coefficient
D_D	The Design Displacement
DO-FPS	Direction Optimized- Friction-Pendulum System
Dy	The Initial Displacement
FPS	Friction Pendulum System
FVF	Frequency Variation Factor
GA	Genetic Algorithms
HDNR	High-Damping Natural Rubber
K_{eff}	Effective Stiffness
LDM	Large Deformation Model
LPR	Lead Plug Rubber
MRPRA	Malaysian Rubber Producers' Research Association
R	The Radius Of The Curvature
SDM	Deformation Model
SFP	Single Friction Pendulum
SREI	Reinforced Elastomeric Isolators
STP	Superstructure Time Period
TASS	TAISEI Shake Suppression

T_{eff}	Effective period
TFP	Triple Friction Pendulum
TFPB	Triple Friction Pendulum Bearing
UPSS	Uplifting sliding bearing
VFPI	Variable Frequency Pendulum Isolator
W	The Structure’s Weight.
β_D	Effective Damping

CHAPTER 1

INTRODUCTION

1.1 Background

Late seismic tremors, especially the 1989 Lorna Prieta and 1994 Northridge quakes in California, and the 1995 Kobe seismic tremor in Japan, have brought about a huge death toll and genuine harm to the property. Numerous a seismic development outlines and innovations have been progressed throughout the years in attempting to mitigate the impacts of quakes on structures and their frail substance. Diminish the effect of extreme ground movements on the structures and their substance is constantly a standout amongst the most people points in the area of common and basic designing and draws in the consideration of various specialists and architects around the globe. The strategy of base separation has been produced in an attempt to ease the effects of structures and their substance through quake assaults and has been guaranteed to be one of the more dynamic strategies for a wide area of seismic outline issues on structures in the previous two decades (Nassani and Mustafa, 2015).

Seismic isolation has the capability to ameliorate the seismic performance of structures via protecting both structural and non-structural elements, effectively submitting safe buildings that also minimize economic damages due to downtime and repair costs. In spite seismic isolation is a mature technology, first performed in 1969, its propagation has been confined in the United States, due to a number of reasons, including intricate design codes and fear on the part of designers and design reviewers. There is a wide assortment of bearings available for seismic isolation. Bearings fall into two prime class: elastomeric (rubber) bearings and frictional sliding bearings. Rubber bearing isolation systems are well researched and prolific all the world. Books such as Naeim and Kelly (1999) and Kelly and Konstantinidis (2011) directory a big body of research on rubber bearing systems. Between rubber bearings there are linear elastic bearings predominatingly used with external energy squandering devices, lead core rubber bearings, crystallizing rubber bearings and rise damping rubber bearings. To preserve stability under large lateral displacements, bearing diameters become large. Increase in bearing diameter results in solider bearings, making isolation of light structures tricky. Contrastingly, the behavior of frictional sliding bearings is nominally autonomous of axial loads. There are two generally used types of sliding bearings: flat sliding bearings, which are used in incorporation with elastomeric systems, and pendulum bearings. Zayas et al. (1987) were the first to propose the single friction pendulum (SFP) bearing (Tracy, 2011).

The bearing consists of a frictional slider baseded on a spherical concave surface. The term pendulum indicates to the motion on the slider on the bearing under excitement. This bearing has a bilinear backbone curve that results from the linear stiffness linked with the pendulum motion and the persistent frictional force. The hysteretic properties of the SFP bearing are identical to a lead plug rubber (LPR) bearing, or linear rubber bearing, in combination with an outer hysteretic devises, but the initial stiffness of the friction pendulum is predominatingly larger and the transition between initial and second stiffness is typically more abrupt in the SFP bearing. In an try to create a more adaptable bearing with smoother move, Earthquake Protective Systems developed the triple friction pendulum (TFP) bearing, The bearing has 4 stacked spherical sliding surfaces, two of which are similar, leaving three distinguished pendulum mechanisms. As motion happens to all four sliding surfaces, the TFP bearing lets for the same displacement capability with a bearing that is lower than half as large in diameter as the SFP bearing. Also that, sudden changes in behavior between sliding and non-sliding stages in the SFP bearing trigger fleeting dynamic responses at the frequency of the supported structure via creating more measured transitions in hardness, the TFP bearing lessen these responses (Morgan and Mahin, 2010).

Chalhoub and Kelly (1990) put a concise introduction to the response mechanisms of base isolated buildings during a two degree of freedom linear system. The influence, of the isolation system to lessen the seismic response is during its capability to shift the base frequency of the system out of the domain of frequencies where the earthquake is sturdy. As well, showed that the extreme important feature of seismic isolation is that it increased elasticity increases the normal period of the structure.

Because the period is increased after that of the earthquake, resonance is averted and the seismic acceleration response is decreased.

1.2 Objectives and scope of the study

The major aim of this thesis is to study the influence of utilizing the friction pendulum isolators to enhance the earthquake response of steel building. The study involves analyses of the seismic responses of isolated structures, which is oriented to grant a obvious comprehension of the processes involved and discussion of different of results among isolated structures and fixed base structures. For this purpose, non-linear dynamic analysis were performed to assess their contribution of FPS in improving the earthquake response. Various friction coefficients were considered for FPS. Computer program SAP2000 was used to model and analyze the structures with and without FPS.

1.3 Outline of the thesis

Chapter 1- Introduction: The aim and scope of the thesis were introduced.

Chapter 2- Literature Review: Previous studies were explained on the earthquake isolation systems. Their effects on the seismic response of structures were given.

Chapter 3- Case Study: This chapter yielded the analytical model of the fixed base and the base-isolated buildings. The seismic isolation system of friction pendulum isolation was described. Moreover, the methodology used in the design and analysis the model was given in detail in this chapter.

Chapter 4- Results and Discussion: Findings obtained from the nonlinear dynamic analysis of the building installed by friction pendulum isolators. 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 Base Isolation Systems

The quake safe structures can be grouped, into inflexible structures and adaptable structures. In inflexible structures, the control strategies that are utilized to withstand greatest burdens are basically to decreaseing the interstory uprooting with the assistance of slanting supporting, the union of shear dividers and the use of composite materials in versatile structures, for example, base-secluded structures, the key control process is to diminish the excitation contribution with the use of dampers and Isolators. The control techniques of inflexible structures were choosed to be seismic tremor risk diminishment exchanges because of enduring decided information and the readiness of advancements correlated to auxiliary harden. Be that as it may, huge interstory float and floor increasing speeds of exceptionally harden structures increment risk of intense harm. of the building, especially under enormous size of the tremor. versatile structures, for example, tall structures can turn away the resounding condition and adequately diminish auxiliary reactions. At the point when structures are constructed in light of to code particulars, they are unsurprising to be decimated through solid seismic tremors yet to Keep standing. This customary procedure to seismic plan is not acknowledged for basic building, for example, doctor's facilities, fire stations, and media communications focuses. The proficient decline of interstory float in the floor of base disconnection frameworks can ensure the most reduced mischief to offices and also human security. The thought of base separation frameworks had been proposed over the most recent couple of decades and the reachable advances and the learning of base isolation frameworks are getting developed and all around decided. Seismic isolation frameworks are more proficient when used to high strength, low-ascent structures, inferable from their ability to adjust the properties of the working from inflexible to versatile. A developing, number of working to be disengaged mirrors the truth that the base separation framework is steadily getting to be plainly satisfactory as a demonstrated innovation in seismic tremor danger diminishment. Base disengagement is an against seismic plan system that can diminish the impact of quake ground movement by means of uncoupling the superstructure from the base. The building can be decoupled from the level elements of the ground movement by means of mediating auxiliary components with low flat strength among the base and superstructure. After look at these structures that accomplished the Kobe seismic tremor in 1995 in Japan, the execution of establishment detached structures, under to a major scale quake has turned out to be stellar as predict. Consequently, engineers have committed tome and research to this matter and the disengagement framework advancements have been very much enhanced and set up as far as hypothesis, outline and building stages. Figure 2.1 presents the mechanism of seismic isolation in multistory buildings (Cheng et al., 2001).

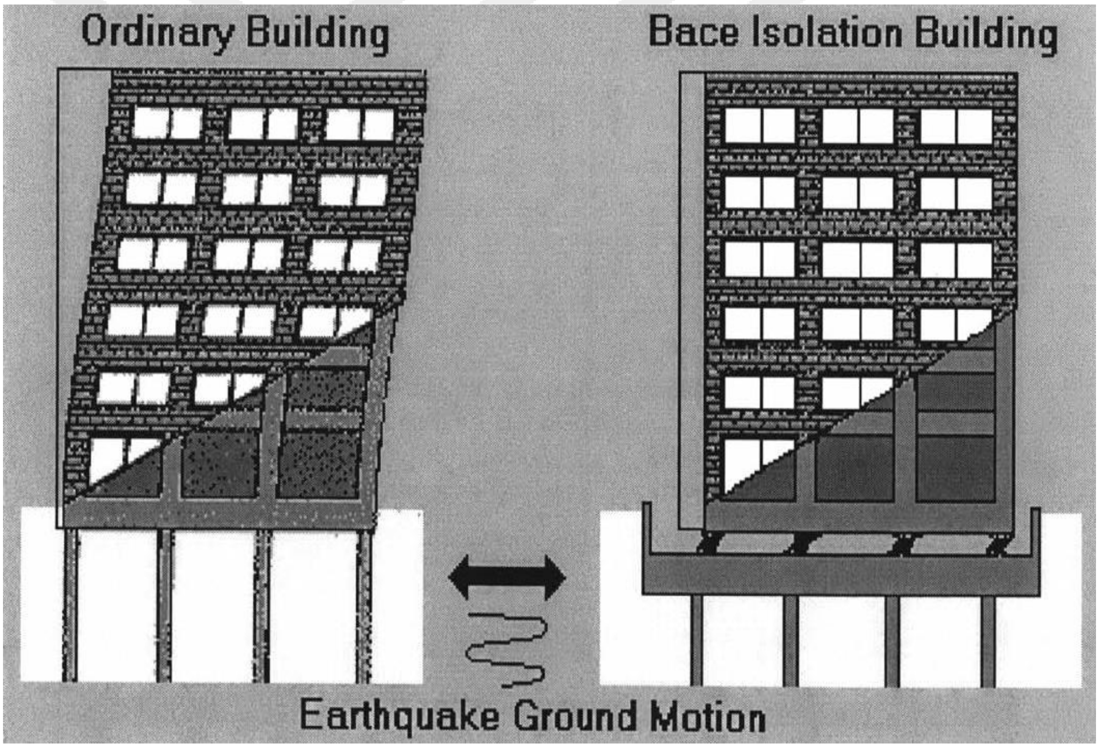


Figure 2.1 Comparison of base-isolated and fixed-based building (Cheng et al.,2001)

2.2 Types of Base Isolation

Isolators are the principle gadgets that are complete in an auxiliary framework for the target of separation. too, dampers can be used in participation with a disconnection framework for vitality dissemination inside the framework. The run of the mill isolators is arranged in Figure 2.2 (Georgios and Antonios, 2015).

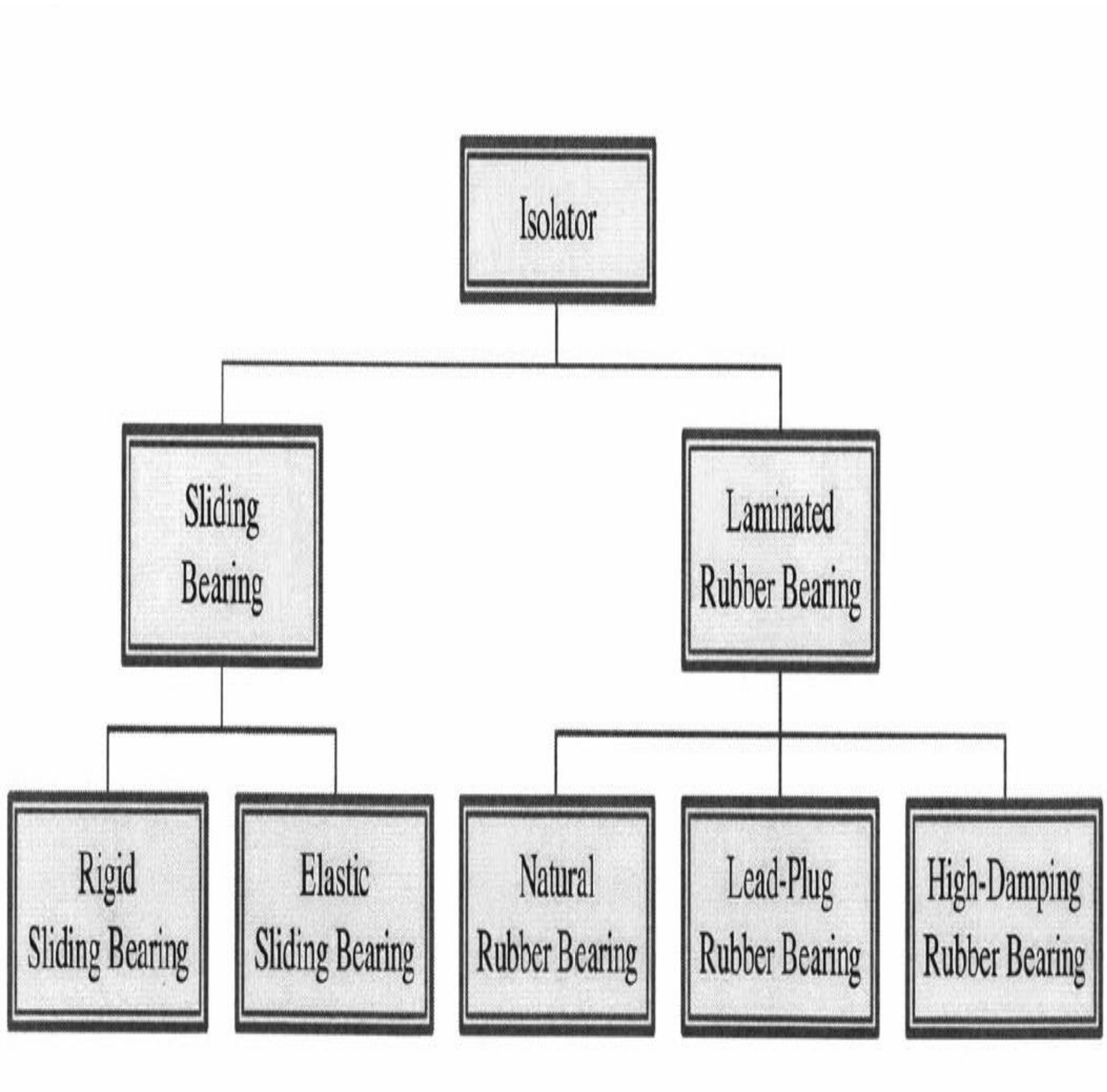


Figure 2.2 The classification of isolators (Cheng et al., 2001)

2.2.1 Elastomeric-Based Systems

The spring and damper components interfacing the building mass to its support are called direction. Considering the essential idea of base detachment framework, we need to make gadgets that can provid helpful strength in vertical bearing and flexibility in flat course. Following quite a while of change, elastomeric course have been created to achieve the different needs of base disconnection frameworks. Figure 2.3 presents the shear deformation of elastomeric rubber bearings (Cheng et al., 2001).

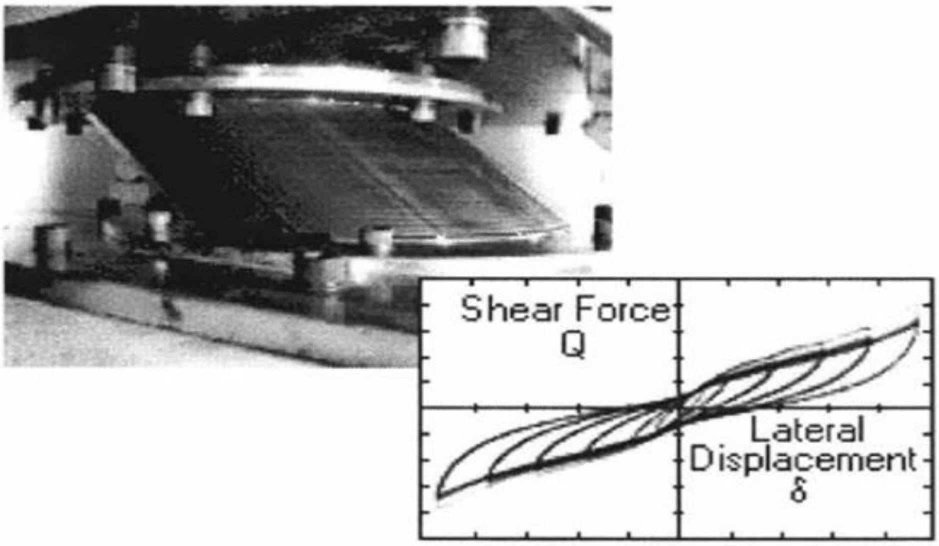


Figure 2.3 The shear deformation of elastomeric rubber bearings (Cheng et al.,2001)

2.2.1.1 Low-Damping Natural and Synthetic Rubber Bearings

This type of seismic isolation has been applied mainly in Japan in coupling, with additional damping devices such as viscous dampers, sliding mechanisms and so on. These insolators have 2 thick steel end plates and several thin steel shims. The rubber is vulcanized and bonded to the steel in a single process under heat and pressure in a mold. The steel shims stoped bulging of the rubber and supply a high vertical solidity. The advantages this kind of seismic isolation has are many: First of all, they are to make (the compounding and bonding process to steel is well known),simple to model and their mechanical response is natural by rate, temperature, history or aging. The only disadvantage is that an extra damping system is needed (Naeim and Kelly, 1999).

2.2.1.2 Lead-Plug Bearings

The lead-plug bearing technology was in vented in New Zealand in 1975 and has been used fundamentally in New Zealand, Japan and United States. Lead-Plug bearings are coated rubber bearings similar to low-damping rubber bearings but include one or more lead plugs that are incorporated into holes. The steel plates in the bearing force the lead plug to deform in shear. The lead in the bearing deforms physically at aflow stress of about 10 MPa, providing the bearing with a bilinear response. It is very important, the lead to be appropriate tightly in the elastomeric part of the bearing, and this is attained via developing the lead plug few millimetres biger than the hole and forcing it in. Before the installation of the lead rubber bearing, it is necessary to specify the displacement at which a specic damping rate is required Figure 2.4 presents Lead-Rubber Bearing Isolator (Georgios and Antonios, 2015).

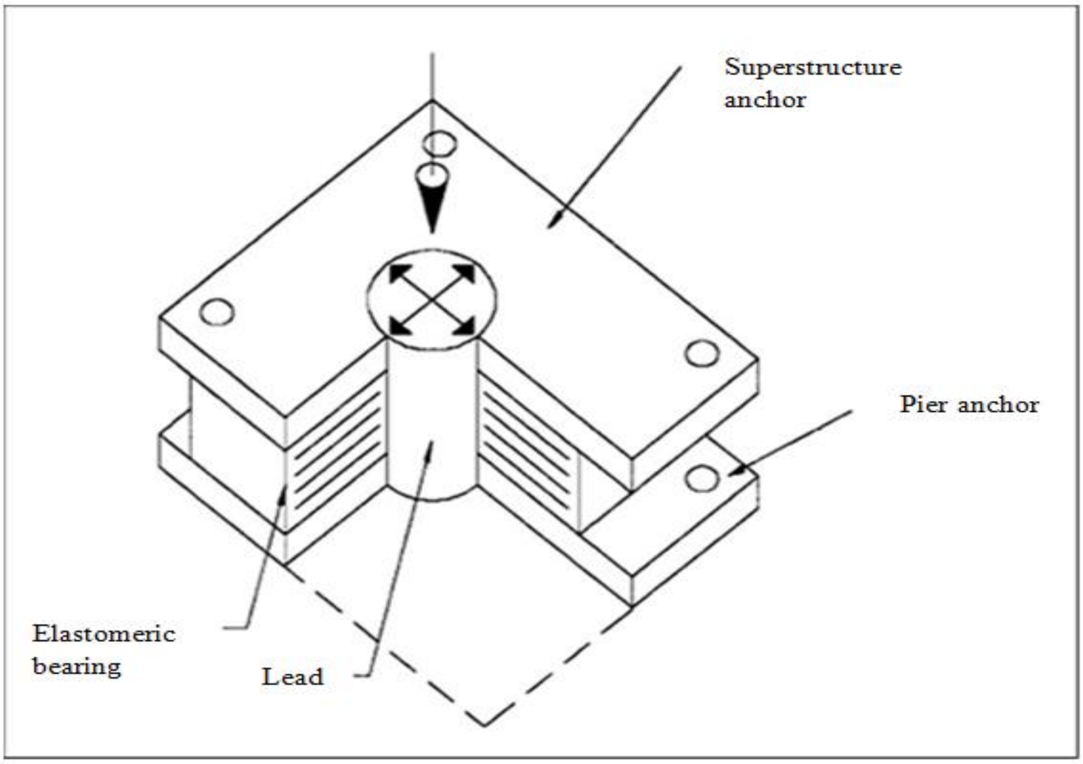


Figure 2.4 Lead-rubber bearing isolator (Georgios and Antonios, 2015)

2.2.1.3 High-Damping Natural Rubber Systems (HDNR)

Malaysian Rubber Producers' Research Association (MRPRA) based in United Kingdom developed a normal rubber complex with enough damping in order to reduce the want for extra damping devices during seismic isolation. By adding extrane carbon block, resins and other   Characteristics filters, damping is increases to levels among 10 and 20% at 100% shear strains and a shear modulus about 0.34 MPa at lower levels of hardness and 1.40 Mpa at higher levels. This specie material is nonlinear at shear strains lower than 20% and is focused more on higher solidity, and damping in order to lower seismic and wind loads. Between 20 and 120% of shear strain the modulus is constant and low and at big strains it rise because of a strain crystallization operation in the rubber which can increase energy dissipation. At large strains, the increase in solidity and damping can develop a stiff system for little input and a linear and exible at design level input. It can also reduce, displacements under unexpected input levels that override design levels (Naeim and Kelly, 1999).

2.2.2 Isolation System Based on Sliding

The base isolation utilize sliding easier to handle strategic system and as well the closest method that have been improved. The basic notion of the sliding system is to decrease the acceleration of land on the shear displacement among the base and the upper structure calculation. This can be carried out via introducing friction in engineering devices. several notices have pointed out that the construction of small buildings cannot be isolated cost effectively by utilize elastic isolators. Thus, sliding more alternate become economic systems for earthquake-resistant solutions. At the same time, sliding systems can structure back to its original location after a seismic happening, which is a unique feature of sliding systems and other kinds of devices may not be able to do it Figure 2.5 presents Schematic Diagram of Sliding System (Cheng et al., 2001).

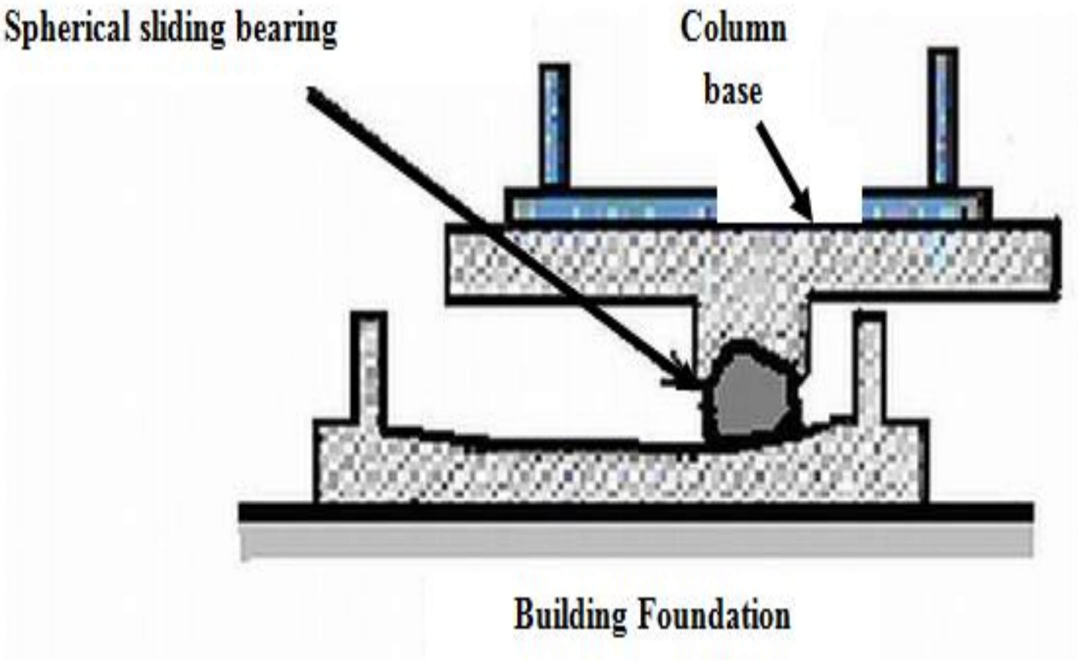


Figure 2.5 Schematic diagram of sliding system (Cheng et al., 2001)

2.2.2.1 Friction Pendulum System

Friction pendulum system (FPS) is the bearing used broadly on the premise of the guideline of sliding framework with a pendulum kind, isolator to supply damping mission use grating. Isolator FPS has verbalized slider mobile on the surface of the erosion circular. It covered the surface of the explained slider in contact with the circular surface of grinding with both self-greasing up composite materials. Is appended to the opposite side of the slider to the sunken stainless steel, spheroid additionally included with the low-contact composite materials. At the point when the slider is proceeding onward the spheroid, it will raise the mass upheld and will give control development of the reclamation of the framework. Under outrageous loads, for example, seismic tremors, and moves the slider along the inward surface, creating the bolster structure to move in little curves like a pendulum. The isolators lessen transmission of the quake powers to the structure by deflectiion (the pendulum motioni) and by rubbing (damping) on the sliders. The sweep of the bend of the inward surface will controls the compelling solidness and the framework time frame. Figure 2.6 presents cross sectional view of FPS Bearings (Cheng et al., 2001).

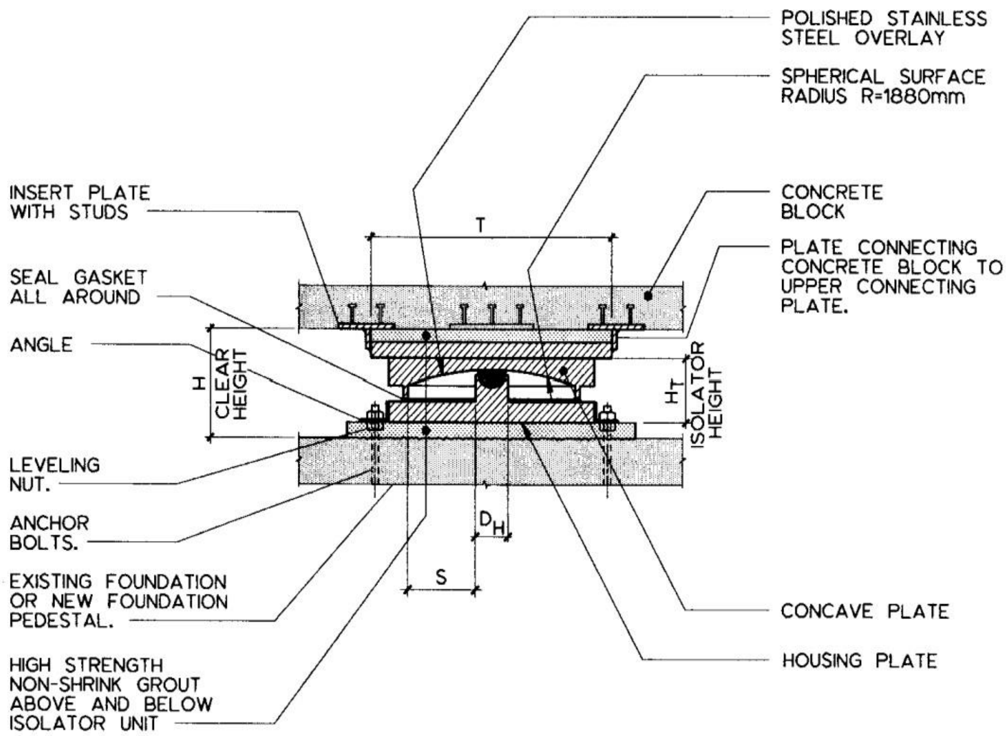


Figure 2.6 Cross sectional view of FPS bearings (Georgios and Antonios, 2015)

2.3 Development of Seismic Base Isolation Systems

A medical doctor named J.A. Calanterients, in 1909, proposed the primary seismic base isolation technique. His disconnection framework was totally in view of sliding. Mr.Calanterients guaranteed that if a structure is based on a fine material, for example, sand, mica, or powder, this fine soil will enable the superstructure to slide amid a quake. Consequently, the flat constrain versatile to the building would be decreased and the structure will be survive the occasion. In spite of the fact that the isolation framework that Mr. Calanterients recommended was a primitive quake safe plan, the fundamental thought behind his strategy is the same with the rationality of seismic base separation today (Naeim and Kelly, 1999).

Early cases of seismic base isolation strategies were made out of sliding storm cellar, balls, sliding rollers and so on. John Milne, who was a Professor of Mining Engineering in University of Tokyo, played out his first seismic base disengagement explores different avenues regarding sliding balls. He started his tests with rollers that are 10 creeps in distance across. In any case, with a specific end goal to enhance the twist resistance of his seismic segregation framework he lessened the breadth of his sliders to ¼ creeps toward the finish of his reviews (Lissa, 2004).

Till the closures of 70's, a couple seismically disconnected structures were built in Japan. It was the improvement of overlaid elastomer isolators that made seismic base detachment a down to earth strategy for tremor safe outline. To begin with, elastic was utilized under building cellars to separate the structures. Steel plates were then vulcanized with elastic so as to expand the vertical firmness of the isolators Figure 2.7. Today steel fortified elastomeric isolators (SREI) are being utilized for seismic base confinement of a few sorts of structures, for example, private structures, administrative structures, spans, mechanical structures, LPG tanks, and so forth. (Naeim and Kelly, 1999).

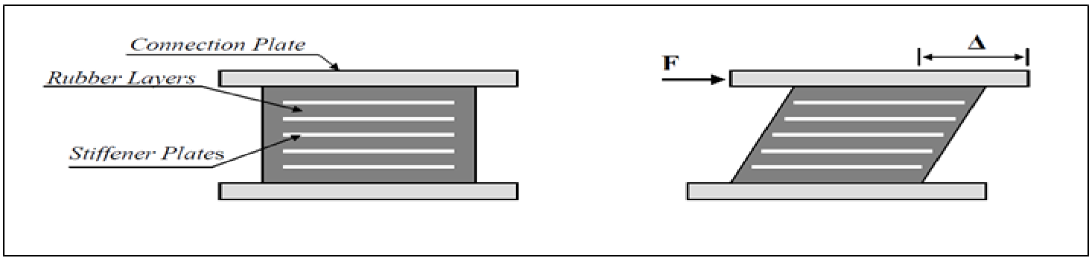


Figure 2.7 Steel reinforced elastomer isolator, SREI (Turer and Özden, 2008)

Lead-plug elastic direction are steel strengthened elastomeric isolators with at least one round gaps as appeared in Figure 2.8. The lead-connect is embedded to these gaps so as to expand the damping of the isolator. Notwithstanding, expansion of damping may build the commitment of optional modes on the structure reaction. This may diminish the effectiveness of the confinement framework. Subsequently, lead-plug elastic isolators are utilized with enough number of SREIs to accomplish the required superstructure reaction (Naeim and Kelly, 1999).

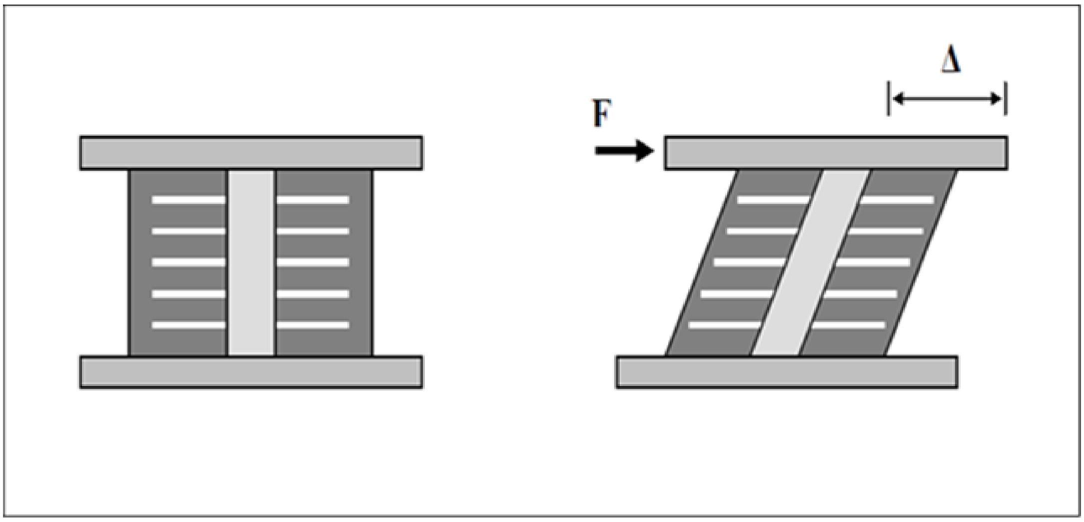


Figure 2.8 Lead-plug rubber bearing (Turer and Özden, 2008)

SREI tests utilized under structures are too substantial as a result of steel plates inside the isolators. This largeness makes both creation and development of elastomeric isolators troublesome. This causes huge increment in the cost of the framework. Keeping in mind the end goal to accomplish this issue, Kelly et al. attempted to utilize lightweight fiber fortification inside the elastomeric isolators (Moon et al., 2003).

Fiber- reinforced elastomeric isolators are a recently presented idea in the field of seismic base separation. Kang et al. scanned for opening and lead plug impact on fiber strengthened elastomeric isolators (Kang et al., 2003).

The flexibility of the fiber material is a variable influencing the pressure modulus of fiber strengthened elastomeric isolators. Tsai, Kelly and Takhirov led splendid trial and investigative reviews on pressure conduct of fiber strengthened elastomeric isolators (Tsai and Kelly, 2002).

Early proposed slidiing-based seismic seclusion techniques were lacking to re-focus the working to its unique area. Zayas et al. studied FPS with a specific end goal to deal with re-focusing lack of sliding rollers. The framework is made out of two inward Teflon circular surfaces with an explained slider inbetween these sunken surfaces. FP is equipped for re-focusing the superstructure to its unique position with the help the flat part of the heaviness of the structure laying on the detachment framework. The vitality dispersal is guaranteed through the grinding between the surface of the curved plates and the enunciated slider that are introduced in Figure 2.9 (Zayas et al., 1990).

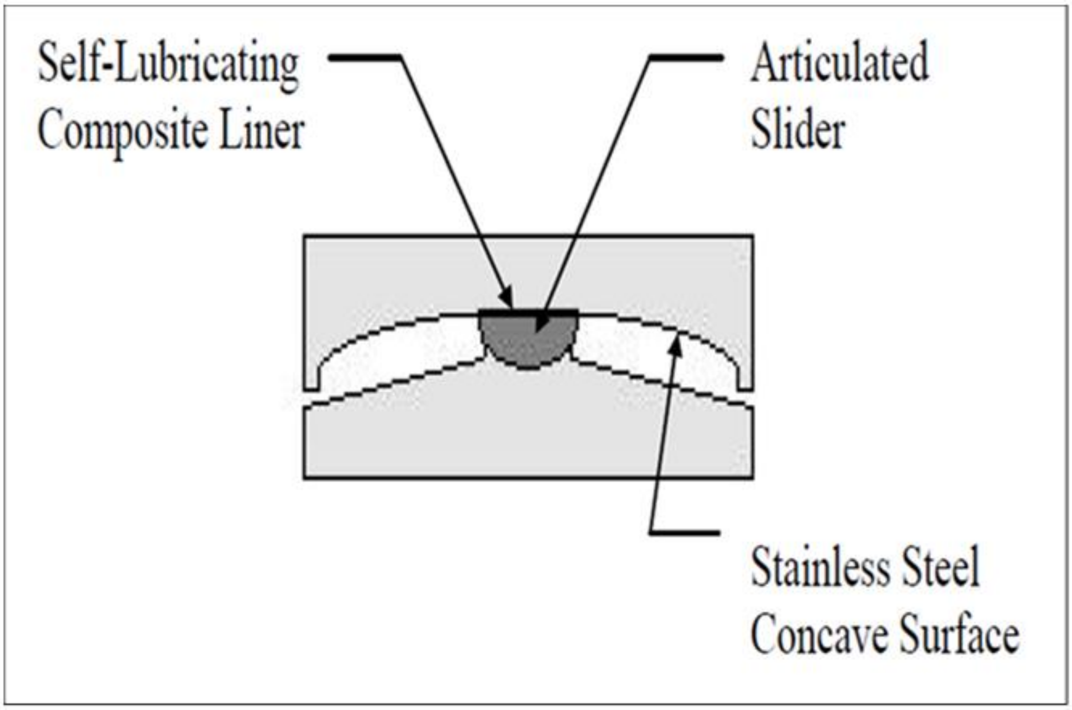


Figure 2.9 Friction pendulum system, FP (Turer and Özden, 2008)

TAISEI Shake Suppression (TASS) framework, the Resilient-Friction Base Isolator System, Sliding Disk Bearing and Helical Spring framework are the other normal reestablishing frameworks used to separate the structures. In TASS framework, parallel elastic pieces give the re-focusing capacity. Versatile Friction Base Isolator framework is made out of Teflon-covered steel plates with an elastic center to empower re-focusing of the disengagement framework. A building disengaged with Sliding Disk Bearing and Helical Spring framework slides on Teflon direction and re-focus to its unique area with the assistance of helical springs. Figure 2.10 presents TASS System (Mostaghel and Khodaverdian, 1987).

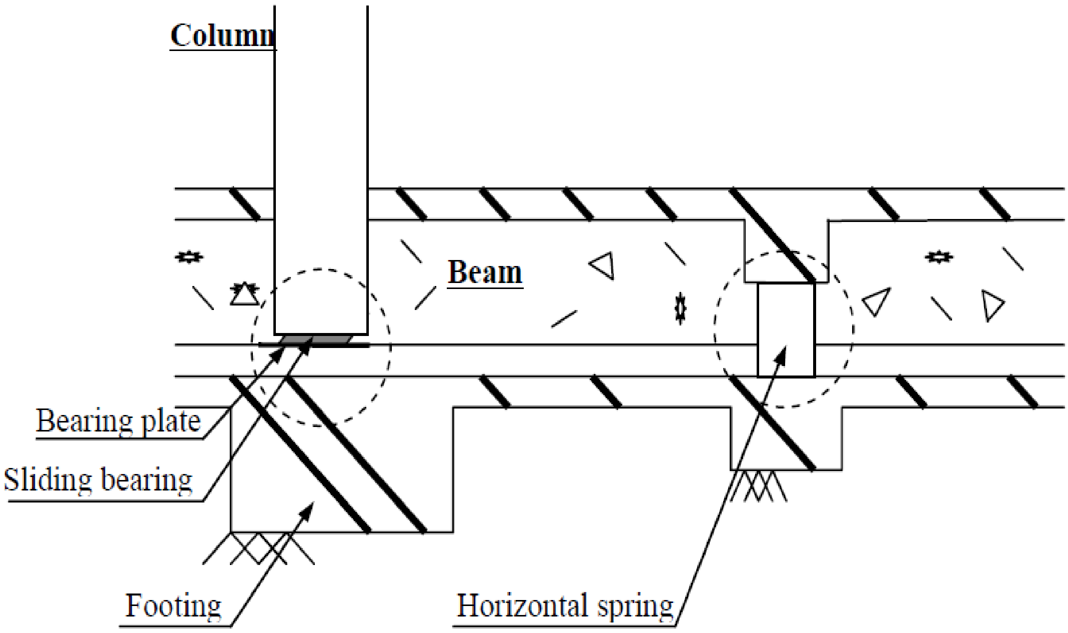


Figure 2.10 TASS system (Turer and Özden, 2008)

A procedure has been applied to develop conditions that gauge dislodging disconnection because of solid ground movement on disengaged structures with contact pendulum framework. The subsequent plan conditions, in view of strict non-direct examination, demonstrate an other option to the refined proportionate straight strategies utilized by means of current U.S. construction standards. The controlling conditions of the framework are reduction to a shape with the end goal that the medium standardized dislodging of the framework because of a troupe of ground movements is found to rely on upon just the disengagement time frame—a component of the ebb and flow of the isolator—and the rubbing power at first slip standardized by means of pinnacle ground speed. The standardization is proficient in reducing the scattering of the standardized dislodging for a gathering of ground movements, inferring that the normal standardized uprooting is a sound gauge of reaction. The outline conditions mirror the enormous (20 to 38%) expansion in uprooting when the fervor include two parallel segments of ground movement then again of only one segment. Identical direct strategies are display to disparage by means of up to 30% the correct normal relocation decided through non-straight reaction history investigation for one part of ground movement, and construction regulations contain at most a 4.4% expansion for a moment segment (Keri and Anil, 2004).

2.4. Friction Pendulum Isolators and Their Use in Building

Triple Friction Pendulum Bearing (TFPB) as a novel seismic isolator, gives distinctive mixes of solidness and damping amid its course of movement. The versatile conduct of TFPBs is one of the useful answers for unsatisfactory execution of seismic confinement frameworks under close blame ground movements. Choosing the TFPB's plan factors (ebb and flow radii, rubbing coefficients and relocation limit of sliding surfaces) is confused process while finding the streamlined blend of these factors relies on upon info ground movement qualities and seismic execution destinations of the superstructure. Here to begin with, careful nonlinear dynamic investigations are performed to recognize effect of the outline factors on superstructure reaction (rooftop increasing speed and removal of detached level). from that point numerical streamlining technique in view of Genetic Algorithms (GA) is connected to characterize the ideal estimations of the plan factors that diminishing superstructure requests. In this operation, close blame ground movements are utilized with area of heartbeat periods and peril levels as information energy. As per GA comes about, the determined immaculate plan factors of TFPB have essentially recognized interims for various reason reactions, for example, story float and TFPB relocation. So reaction purposes (single target capacities) are joined to make another wellness work. The proposed advancement strategy for characterizing plan factors and outline interims can be used for examining numerous different sorts of superstructures with indistinguishable practices (Hesamaldin and Touraj, 2014).

during a compare between various Samples of isolator seismic shown the influence the isolator seismic response . The investigations have been performed considering an arrangement of ground movements with close field records recognize through different estimations of the proportion between the pinnacle vertical and level increasing speeds. The records have been in like manner connected considering expanding estimations of power. The outcomes have exhibit that a right examination of the reaction requires to consider a model that record for the disparity of the erosion in the isolator with speed and typical constrain. The models in light of steady grinding have given outcomes practically equivalent to those with changeful grating when an esteem adjacent to the most extreme rubbing coefficient has been embraced without fall, the vertical seismic part and the pivotal constrain varieties have affected increasingly the greatest level drive, in the request of 15%, than the greatest uprooting. Then again, the examinations for expanding estimations of seismic power have call attention to the impact of the vertical segment on the isolator fall. With a few records, the vertical part decided drag in the isolators before arriving the most extreme relocation demonstrated by means of the maker. These outcomes have show the centrality of building up a plan methodology for the FPS frameworks that can produce into respect the results of the vertical seismic segment. Along these lines it is conceivable to deflect an over valuation for the most extreme quickening tolerable by means of the disconnection gadgets. Disregarding the vertical segment has decided, now and again, estimations of crumple speeding up that are in like manner two times more noteworthy than considering the vertical component (Luca et al., 2016).

As of late, a kind of straightforward and cost productive sliding isolator, specifically the elevating sliding bearing (UPSS), had been created for guarantying the seismic execution of multi-traverse consistent scaffolds. The reason for existing is to control the vast even uprooting of the customary elastic heading utilizing this new sliding gadget which has a high plausibility in diminishing the level dislodging because of the uniqueness of its geometrical design. The UPSS gadget comprises of various sliding surfaces associated together, in view of the PTFE and SUS interface; one even and two slanted surfaces. This review means to examine the ability of utilizing the numerous slider bearing in light of the idea of UPSS to disengage multi-story shear sort structures. The standards of operation and drive uprooting relationship for the isolator are presented. The seismic conduct of the base secluded building by means of the different slider bearing subjected to seismic energy is examined, contrasting and customary elastic bearing and immaculate rubbing slider segregating frameworks. Moreover, careful parametric examinations are performed keeping in mind the end goal to accomplish an immaculate execution of the isolator concerning three fundamental attributes which decide the gadget: leeway length, the inclination edge and the contact coefficient. The outcomes exhibit the adequacy of the numerous slider bearing in diminishing the harm from tremors. The different slider bearing demonstrates to have a high potential in diminishing the impact of the ground relocation beats amid its operation component and its novel trademark that allows the utilization of different arrangement of contact coefficients on each sliding surface.

Furthermore, a rule to decide the ideal estimation of the grating coefficient is created (Muhannad and Akira, 2012).

To secure structures against solid seismic tremors disengaging gadgets, which are embedded among the building and the establishment, can be used. The gadgets demonstration under outside powers as inflexible associations and under seismic tremors as safeguards. A base isolator with solidifying conduct under developing stacking has been produced for medium-ascent structures (up to four floors) and destinations with calm quake risk. Taking after the development of the isolator, the conduct of a model has been explored in the lab under unique burdens. In view of the test comes about the direct proportional solidness and damping qualities of the gadget are resolved and a preparatory numerical examination of the dynamic conduct of the isolator is explored for ten real seismic tremor movements of the Greek Mediterranean district. The investigation demonstrated the efficacy of the device in the decrease of the acceleration response for most seismic under studied. In order to obtain alot factual results, the constitutional and dynamic properties of the building, also the actual nonlinear parameter of the isolator have to studied in the analysis (Pocanschi and Phocas, 2007).

Small scale "hands-on" experience was studed on a paradigm wooden frame building under dynamic influence. The foundation excitement was utilized to the sample via a "home-made" shaking table as shown in Figures 2.11 and 2.12. The device is able of present harmonic movement at the foundation level of the sample building. Two alternate building framework have been designed a rigid framework and a flexible framework. The displacement responses derived from the exams were Comparison with linear time history analysis. The analytical Sample is able of Pick up the occurred displacement values. Harmonic tests were conducted in the second phase of the study on the frame structure used in small scaled seismic devices. In order to isolate the structure supported via the harmonic exclusion, the seismic isolates were selected as the pendulum bearings that are Connected among the building and its basis. Design of building with the FP technology is cost-effective,, since the isolated building behaves elastically through the earthquake movements without any frame damage. The base isolation device having the properties of a pendulum tends to Reduction dynamic forces with the increase the normal vibration dated of the secluded building as shown in Figure 2.13. The exam results offered that displacement and the acceleration responses of the isolated building were big low (Özsoy and Özkaynak, 2017).

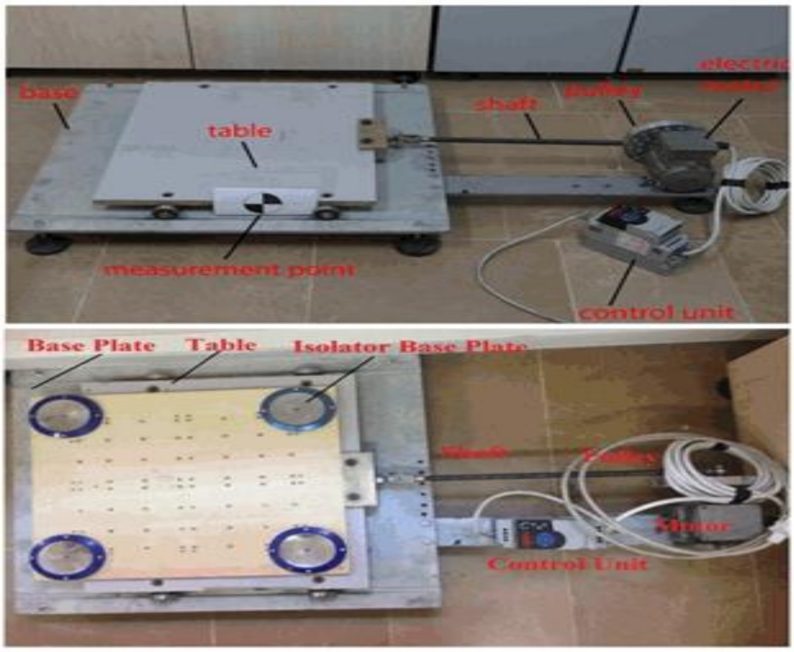


Figure 2.11 General scheme of the shaking table for the fixed based and isolated structure (Özsoy and Özkaynak, 2017)

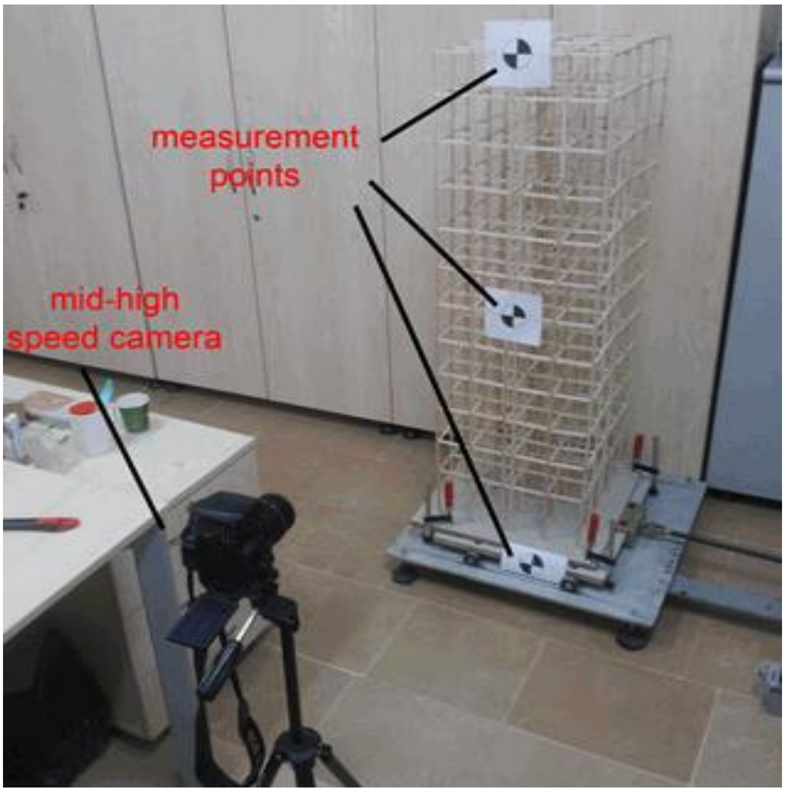


Figure 2.12 Data collection system (Özsoy and Özkaynak, 2017)

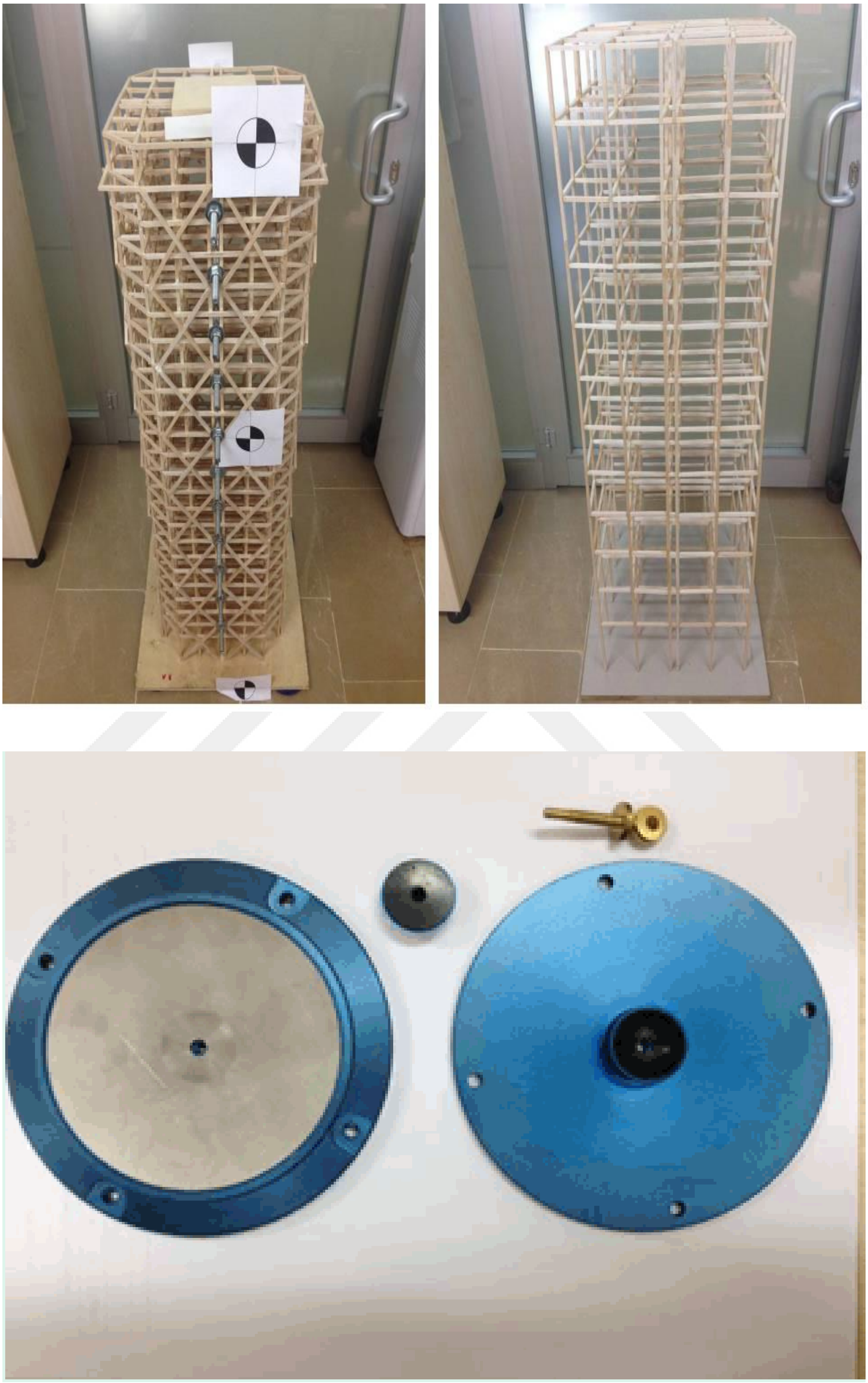


Figure 2.13 General view of rigid and flexible model structures and implemented scaled isolator (Özsoy and Özkaynak, 2017)

In the work of Jangid (2005), the analytical earthquake response of multi-story structure isolated via the (FPS) is scrutinized under near-fault motions. The superstructure is optimality as a linear shear kind elastic sutructure. The controlling equations of movement of the isolated building framewwork are derived and the response of the framework to the natural ingredient of 6 recorded near-fault movements is estimated via the step-by-step process. The difference of upper story ultimate acceleration and sliding displacement of the separated structure is plotted under various framework parameters like superstructure elasticity, isolation time and friction coefficient of the FPS. The compare of results specified that for minimum values of friction coefficient there is important sliding displacement in the FPS under near-fault movements. as well as, there as well exists a special value of the friction coefficient of FPS for which the upper story ultimate acceleration of the structure acquires the lower value. Moreover, the idealized friction coefficient of the FPS is derived from various framework parameters under near-fault motions. The standard chosen for idealized is the lower of each the upper story acceleration and the sliding displacement. The idealized friction coefficient of the FPS is Determined to be at the limit of 0.05 to 0.15 under near-fault movements. as wellas, the response of a bridge seismically separated via the FPS is as well scrutinized and it is Determined that there exists a special value of the friction coefficient for which the pier base shear and deck acceleration acquire the lower value under near-fault movements..

In the study of Zuhair and Israa (2010), they provides an analysis of specific elements of building a multi-storey non-insulated and insulated insulation system base pendulum friction exhibition of earthquakes are real different (El Centro & Loma Prieta) and compared with the process of available results where Aatta system used comparable results as noted as a result of isolation, a significant reduction aggressively cut the base. It was taking three different values for each of the coefficient of friction (0.08, 0.15, 0.25), The radius of the concavity (40in, 80in, 400in) to study the base shear and friction pendulum displacement system. The results showed that the system pendulum friction significant improvement has a kinetic response to the model of the building to reduce the base shear and increased quell the building. By studying the effects of three coefficient of friction (0.08, 0.15, and 0.25) have been carried out with radius of concave 40 in for every kind of earthquake. As a result of comparison between curves, it has been appear that the greater the friction coefficient the later the isolation mechanism is scrutinized. In an ultimate cases the base shear force does not overawed the friction force. In that a case, an isolated fameword responds the identical as a traditional fixed-base frameword as shown in Figure 2.14

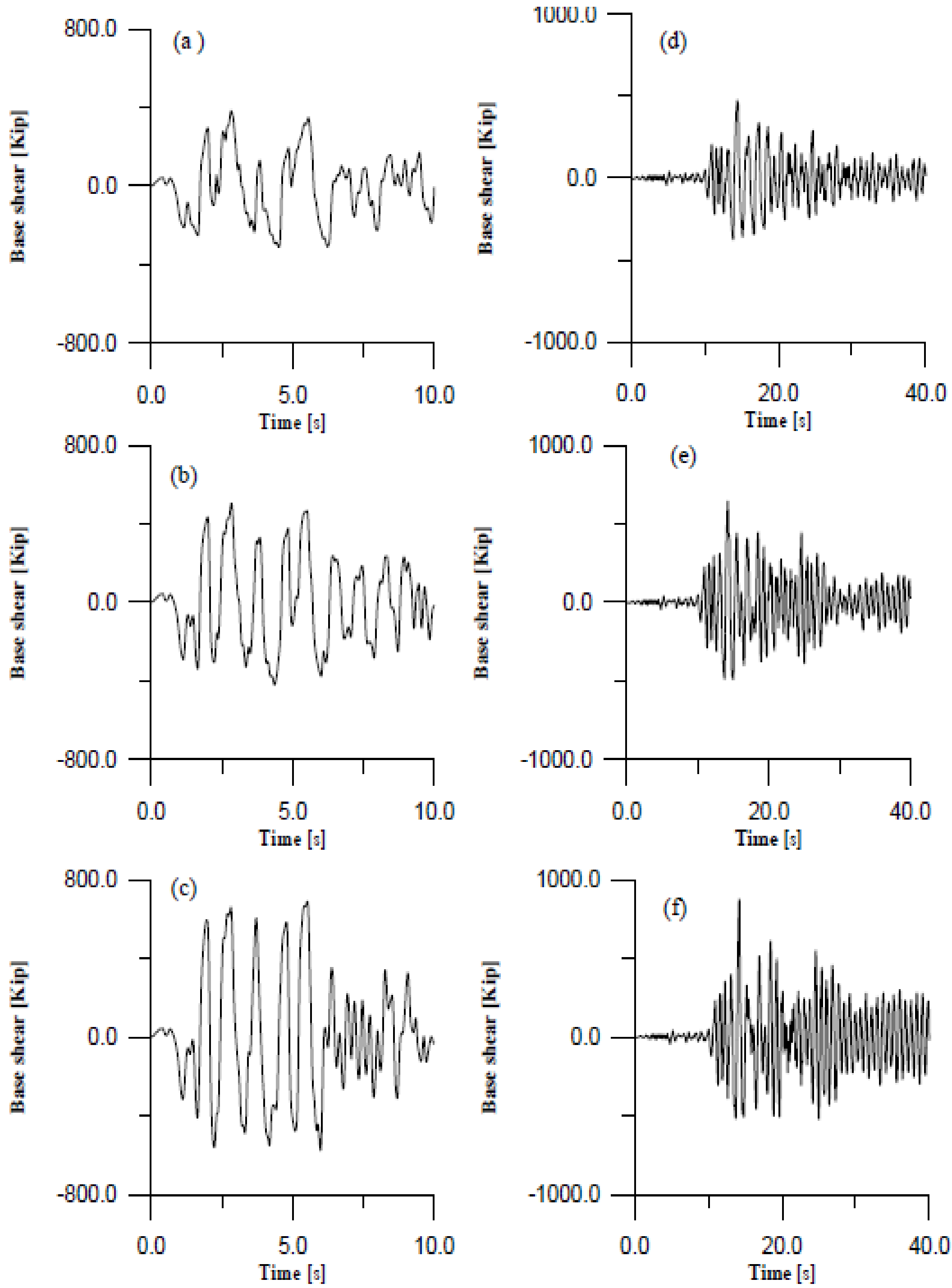


Figure 2.14 Base shear for 3 story building isolated by FPS with different coefficients of friction (a) 0.08 (b) 0.15 (c) 0.25 under El centro and (d) 0.08 (e) 0.15 (f) 0.25 under Loma Prieta (Zuhair and Israa, 2010)

The displacement of friction pendulum system decreases with the augmentation in the coefficient of friction due to increased the damping of the system as shown in Figure 2.15. The same sample as in the previous with a friction coefficient of 0.08 is analyzed for three various radius of concave 40, 80 and 400 in for each kin of earthquake.

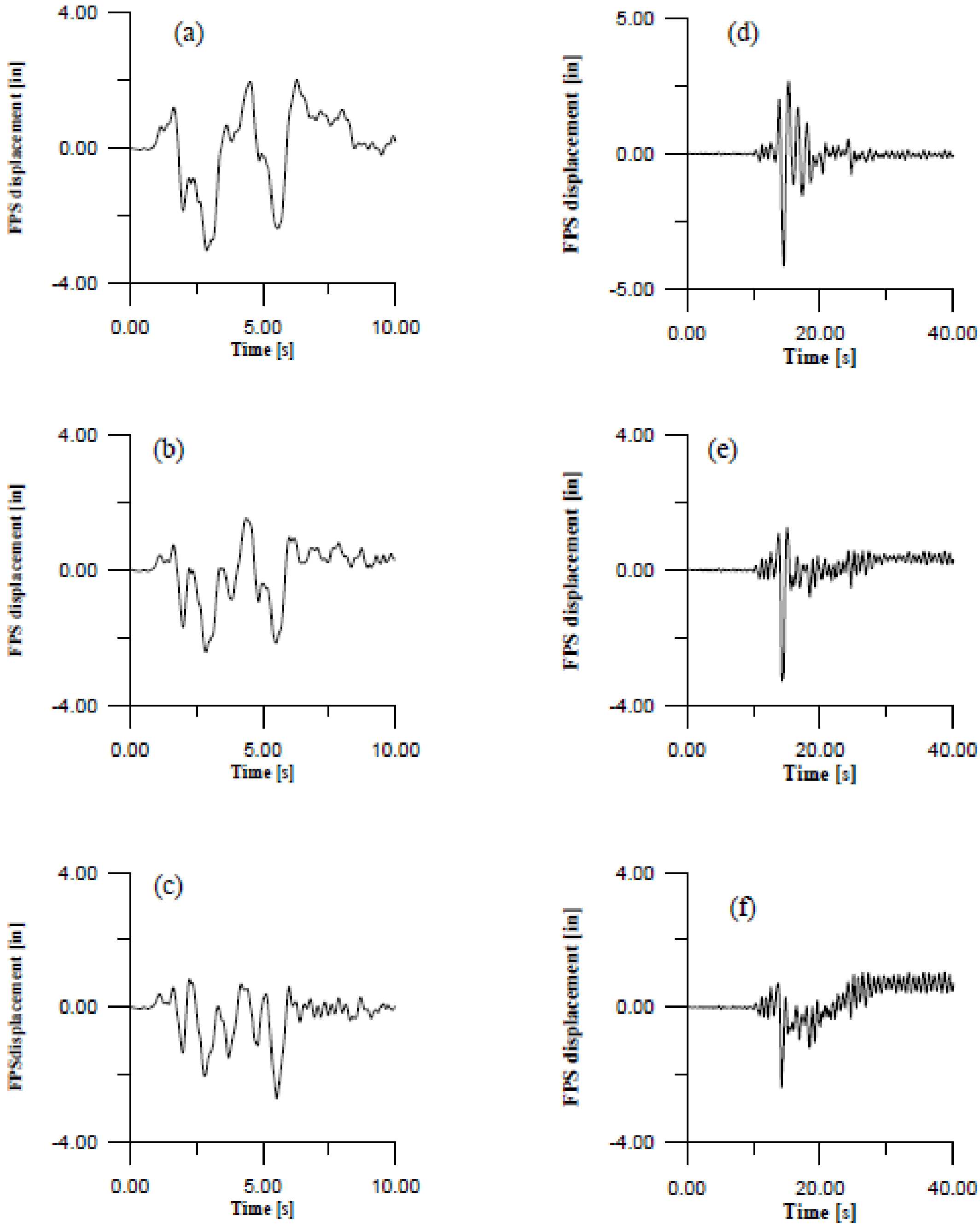


Figure 2.15 FPS displacement with different coefficients of friction (a) 0.08 (b) 0.15 (c) 0.25 under El centro and (d) 0.08 (e) 0.15 (f) 0.25 under Loma Prieta (Zuhair and Israa, 2010)

The base shear reductions with the growth in the radius In that a case, when the radius access to infinity an isolated framework responds the identical as a traditional roller support as shown in Figure. 2.16. A a lot of concaved sliding surface with hence greater geometrical solidity,, decrease the constant displacement of the bearing as shown in Figure 2.17.

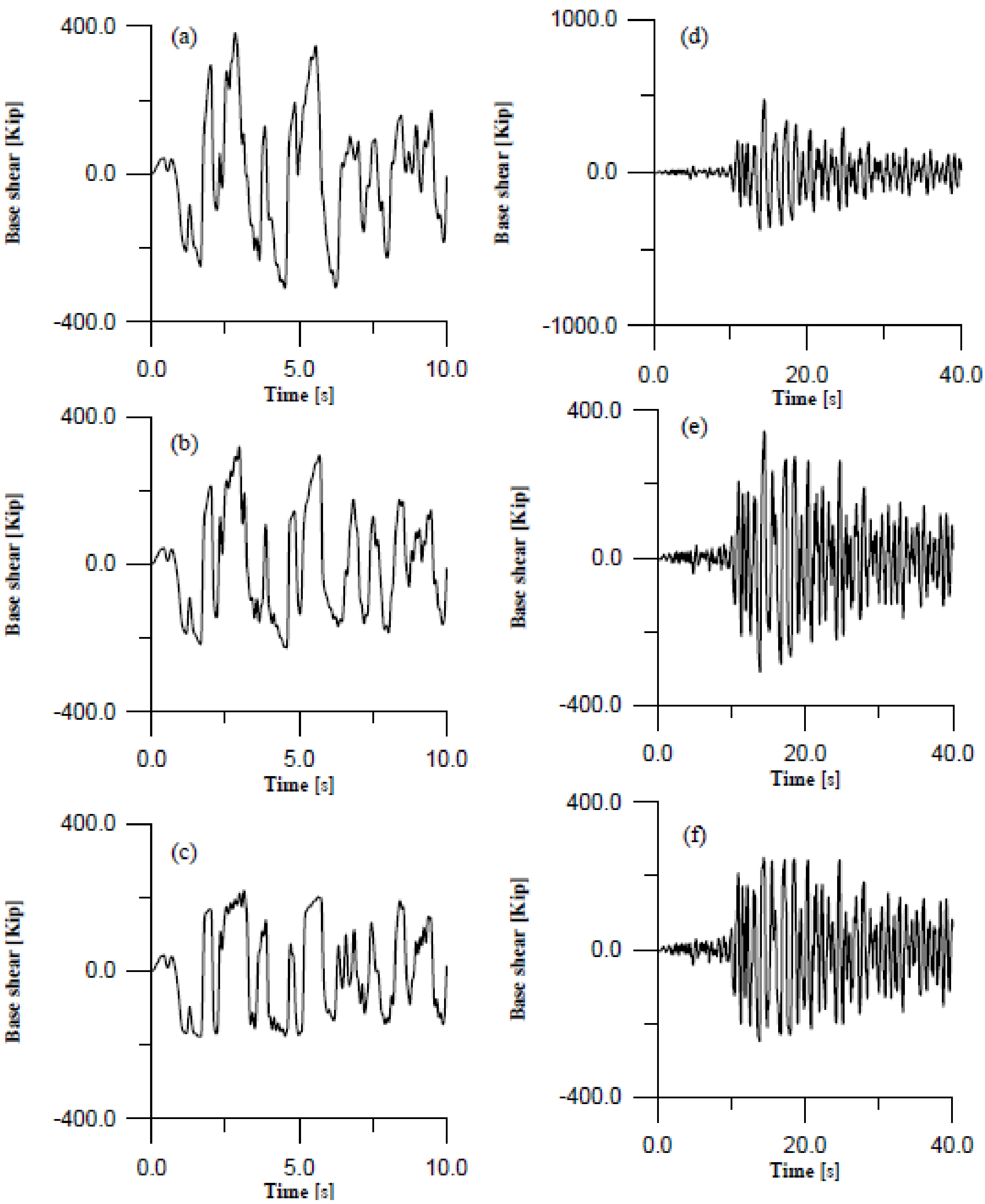


Figure 2.16 Base shear for 3 story building isolated by FPS with different radiuses of concave surface (a) 40 in (b) 80 in (c) 400 in under El centro and (d) 40 in (e) 80 in (f) 400 in under Loma Prieta (Zuhair and Israa, 2010)

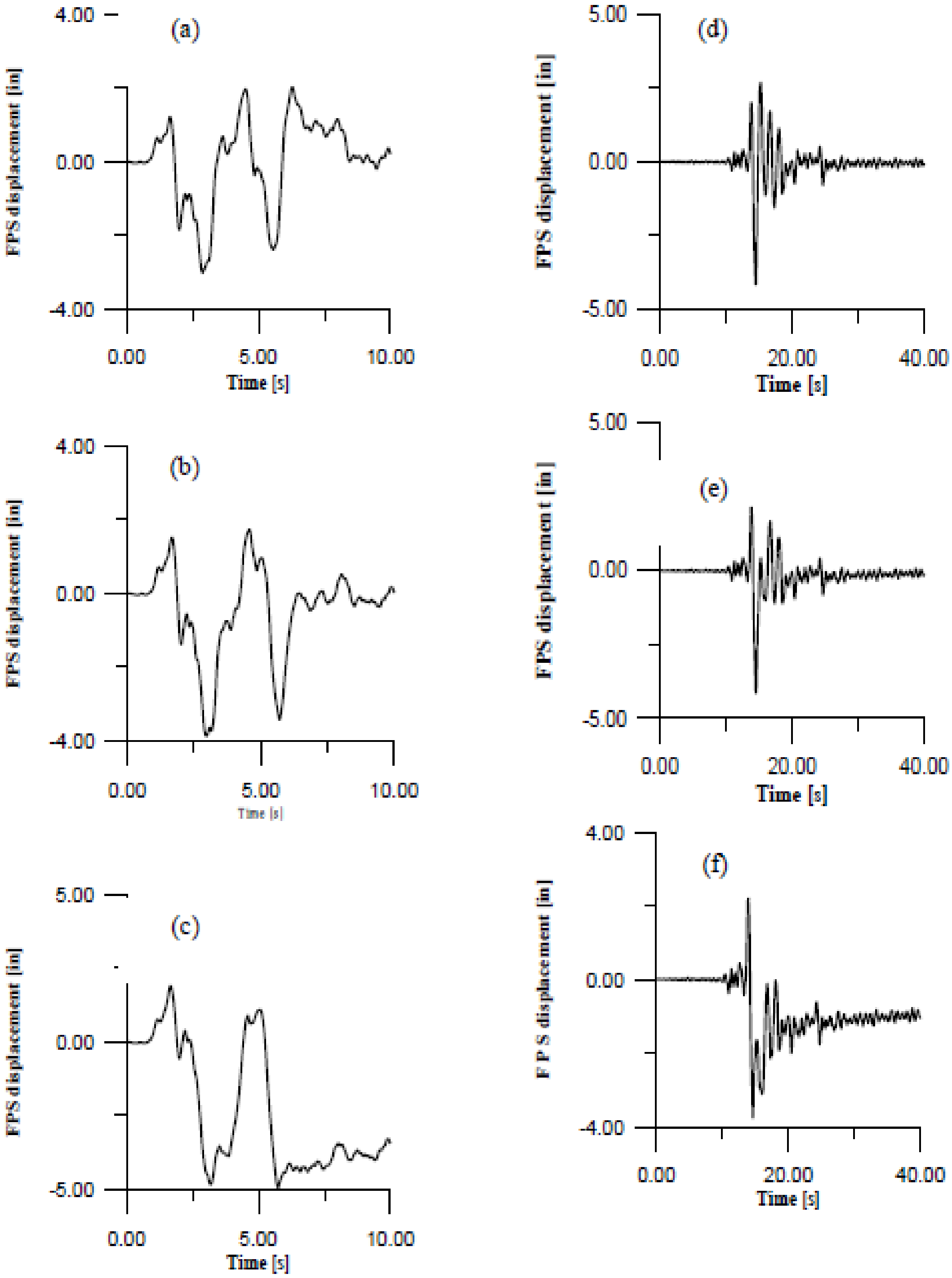


Figure 2.17 FPS displacement with different radiuses of concave surface (a) 40 in (b) 80 in (c) 400 in under El centro and (d) 40 in (e) 80 in (f) 400 in under Loma Prieta (Zuhair and Israa, 2010)

In the study of AI-Hussaini et al. (1994), shake table exams were showed on 6 and 7 floor structure Samples with friction pendulum seismic isolators built-up at the bases. The building models included moment and braced structere, with various isolator composition arrangement, inclusive isolators fixed straight at the foundation, of the first floor columns. Realistic framing specifics representative of full size structures were utilized. In all status, the isolators provided the required and predicted decreases in story shears and drifts. The most important conclusions from their study may be summarized as:

- The friction pendulum isolators decreasing building shear forces and inter story drifts in the multi-story structure Samples via factors of 4 to 6, let the top building framework to stay flexible through sharp seismic loadings. The reductions in drifts big reduce damage to non-structural and structural building elements caused via earthquake ground shaking.
- The installation of the isolators at the foundations of the solo first floor columns, as compared to under a rigid diaphragm base, does not greatly impact the behavior of the isolation bearings or system. The articulated joint of the Friction Pendulum isolators fits the desired joint rotations with no impact on the isolator properties.
- When isolators are installed at the bases of cantilever columns, various isolator displacements are observed at various column locations. The variation in isolator displacements are little in comparison to the total isolator displacements. The proportional differences in isolator displacements have no measurable impact on the comprehensive response of the isolation framework or the higher story shears and drifts. The variation in displacements can be represented for in analytical models which include the flexibility of the frame members.
- Bracing the column bases together attain equal displacements in the isolators, but does not impact the comprehensive response of the isolation framework or the higher building.
- The story shears and drifts occurring in the upper structure are influenced via the shear stiffness of the framing in the isolation story. The story shear stiffness of the framing in the isolation story impact the dynamic properties of structure, and have to be inclusive in the analytical model of the isolated structures. Analytical models which involve the flexibility of the framing in the isolation story can fully account for the response of the isolation story and maximum structure responses.

- The response of the first three modes of the upper structure fully accounted for the response of the experimentally spotted structure shears and drifts, with variances of typically minimal than 1 % as compared to the experimental outcome. The inclusion of only two modes led in variance as large as 5%, and the inclusion of only 1 mode resulted in divergence as large as 23%.
- Summit floor spectra responses within the isolated structures were reduced via a factor of eight as compared to summit floor spectra responses occurring in the non-isolated structures exposed to equal force loadings.
- The response of the isolated structures exposed to severe earthquakes can be strictly foretell via analytical procedures. This is imputed to the well quantified and expected dynamic response of the friction pendulum isolators, and that the upper structural system residual elastic. The response of non-isolated structures exposed to equal force ground motions is considerably less predictable due to suspicion linked with the inelastic response of the structures.
- Local divergence of vertical loads on the isolators does not have any measurable impact on the comprehensive response of the isolation system or the upper structure story shears and drifts. Increases in bearing hardness resulting from increases in vertical load are directly recompense for via equivalent decreases in bearing hardness resulting from decreases in vertical load.
- Local uplift of individual isolators during the structural frame does not have any measurable impact on the comprehensive response of the isolation system or the upper structure story shears and drifts. The Friction Pendulum isolator bearings were unaffected and undamaged via the local uplifts.
- The use of displacement restraints, or displacement limits, were spotted to be an active means to reduction isolator displacements, and insure isolator stabilization, in the event of maximum seismic events significantly override the design event. participation of lateral displacement restraint increases the structure shear forces, but keeps a favorable response in the isolation system and structure. Even in maximum overload cases where participation of the displacement restraint increased base shear forces via 70%, the resulting structure forces were still only 27% of those occurring in the equivalent non-isolated structure undergo to the same earthquake loading. Without a

displacement restraint, isolated structures exposed to equivalent overloads can become unstable and collapse.

- proportionate results were achieved in the isolation system response during the test program which included above 60 seismic tests. The isolator bearings kept their authentic stiffness and energy dissipation characteristics and needed no mend at the conclusion of testing. Isolator responses spotted at the end of the test program were equivalent to those occurring at the beginning of the test program.

In the study of Khloud et al. (2015), the advantages of the application base isolation in the 40-floors steel office structure were obviously demonstrate via the results of a project employed, inclusive:

- Lowering of story accelerations, in-story drifts and base response via larg than 90% percent.
- Amelioration of building earthquake execution levels.
- Reduction the coefficients of friction of the TFP bearings is the maximum efficient means to ameliorate earthquakes representation (i.e. decrease the superstructure’s response values, overall story accelerations and in-story drifts) when performance base isolation in a rise, elastic structure.
- Employed TFP bearings with graeter radii of curvature (R) drive to alot of elastic (lower lateral solidity) isolation framework and develop earthquakes represent, in spite of greater bearing volumes are as well alot of cost.
- Isolator framework competence in diminishing floor displacement, in-story drift, floor acceleration and base response was commensurate to seismic volume; and if 2 EQ have the identical volume, then effectiveness of isolator were reversely commensurate to movement acceleration.
- Isolator framework activity in lessening base responses were larger than its effectiveness in lessening in-story drift, floor acceleration.

In the study of Tsai et al. (2008), an developed base isolation framework suggested the (DO-FPS) is proposed and scrutinized to locate its mechanical behavior during finite Ingredients formulation and study its activity in earthquake reduction via Procedure the shaking table exam. Depended on finite Ingredients formulation, we conclude that the normal period, the ability of the bearing displacement and damping influence for a DO-FPS isolator shifting continually through seismics . So, DO-FPS can avert the resonance and Supply an efficient ability for bearing displacement and damping through the seismics. same time, the shaking table exam as well clarify that DO-FPS have outstanding earthquake reduction abilities.

Jose and Juan (2002) developed to analyze the analytical model based isolators of the FPS that suffer from major distortions and implementation structures. The model presented can be easily executed in a identical form For those found in presently obtainable software packages such as SAP2000. Results acquired of the implementation of this Samples in the analysis of seismic response exposure to movements earth rushing structures appear that the small deformation model (SDM) might command to differences of up to 20 percentage in amounts universal response and more than 50 percentage in the amounts domestic response, like a natural strength in isolators or distortions interstorey. Therefore, it is concluded that the large deformation model (LDM), have to utilized, in the styling of building exposed to afford big distortions in the isolation framework such a result of movements of earth rush.

Vasant and Jangid (2004) studied the effect of isolator properties parameters on the earthquake response of multi-story base-isolated buildings is studed. A comparison of the response of the separated building for equal linear and bi-linear force-deformity behavior of the isolator is made. as well as, the influence of the Form of isolator loop and superstructure elasticity on the earthquake response of the base-isolated building are as well scrutinized. From the direction of the results of their study, the following were extraction are :

- The code particular equal linear elastic–viscous damping sample for a bi-linear hysteretic sample of the isolator under-expectation the superstructure acceleration and over-expectation the bearing displacement.
- There is a big variation, in the frequency content of superstructure acceleration of base-isolated building expectation via the equivalent linear and bi-linear isolator samples.
- The response of base-isolated building is big affected via the form and parameters of the bi-linear hysteresis loop of the isolator.

- The base isolation framework with very minimal yield displacement (i.e. sliding kind isolation frameworks) transmits more seismic accelerations into the superstructure related with rising frequencies. This phenomenon is not Expected via the equal linear Samples of analysis.
- The elasticity of superstructure excess the superstructure acceleration. Nevertheless, the bearing displacements are not much affected via the superstructure elasticity.

Landi et al. (2016) investigated the effect of the design of the isolator earthquake response on the global response of the building has been scrutinized during a rapprochement between various samples. The analyses have been performed considering a set of earth movement with near field records Featuring via various values of the ratio among the top vertical and horizontal accelerations. The records have been as well employed considering growing values of intensity. The results have appaer that a right evaluation of the response demand to study a sample that computation for the difference of the friction in the isolator with velocity and natural force. The samples depends on continuous friction have supplied results identical to those with changing friction when a value near to the utmost friction coefficient has been applied. The results have highlighted as well the significance of improving a design process that can take into considering the effect of the vertical earthquake ingredient. In this case, it is probable to avert an overestimation of the utmost acceleration probable via the isolation devices. ignore the vertical component has specified, in some cases, values of collapse acceleration as well two times greater than considering the vertical ingredient.

Castaldo and Ripani (2016) conducted to evaluating the optimal properties of friction pendulum bearings to be employed for the seismic protection of elastic isolated structural systems under earthquake excitations with different characteristics in terms of frequency content. A two-degree-of-freedom model is considered to describe the isolated system behavior while accounting for the superstructure flexibility and a non-dimensional formulation of the governing equations of motion is employed to relate the characteristic parameters describing the isolator and structure properties to the response parameters of interest for the performance assessment. Seismic excitations are modeled as time-modulated filtered Gaussian white noise random processes of different intensity within the power spectral density method. The filter parameters control the frequency content of the random excitations and are calibrated to describe stiff, medium and soft soil conditions, respectively. Finally, multi-variate regression expressions are obtained for the optimum values of the friction coefficient that minimize the superstructure displacements relative to the base mass as a function of the structural system properties, of the seismic input intensity and of the soil condition.

Ioannis and George (2016) suggested a studed for extraction the total equations of movement to counting an isolator’s displacement becouse to strong earth movement is used to buildings isolated with FPS. The resulting equations, which have the vertical inertia forces, were calculated to assessment the effect of these forces on the isolator’s behavior. The nonlinear equation is solved utilize the technique of sequential approximations. The results acquired appear that the effect of the vertical inertia forces on structural response is small for the case of a long-distance earth movement, whilst becoming important for a near-source earth movement. from another side, very little values of the isolator’s radius R due an rise of the aforementioned effect.

Fadi and Michael (2010) scrutinized the veracity and precision of simplified methods of analysis for structures with TFP earthquakes separated, a framework that showed intricate behavior with capacity based on solidity and force. The simplified analysis process studed is the one normally depicted in codes and determinations. The process is depends on demonstrating the the separated building as a single-degree-of-freedom framework with linear solidity and linear viscous damping equal, respectively, to the efficient or secant solidity and efficient damping of the isolation framework. The review thought about the aftereffects of nonlinear dynamic response history analysis with results of simplified analysis utilizing two sets of earth movement that were scaled to match design spectra in the long period range and after that scaled to appear tremors of various forces. 9 various arrangements were examined, every one of which in all conceivable uprooting administrations of the of the TFP isolator. The review prompted the conclusion that the disentangled strategy for examination (a) by and large under-predicts the pinnacle speed by as much as 35%. The rate measure of underestimation of the pinnacle speed expanded with expanding powerful time of the confinement framework. The best overestimation of dislodging via the improved strategy happened in instances of operation of the isolators in administration V, where important solidify happens. When the simplified process big overrate (via around 35%) the displacement or big disregard (via around 35%) the velocity, the stipulation were such that the simplified process of analysis would not be pliable via viable criterions such as ASCE (important solidify of isolators, extremely solid seismic excitation or efficient period override 3 s).

Panchal and Jangid (2008) examined the seismic representation of a elastic one-story structure separated with a (VFPI) under near-fault and far-field earth movement is scrutinized. The frictional forces mobilized at the interface of the VFPI are supposed to be velocity based on. The interaction among frictional forces of the VFPI in two horizontal trends is properly studed and connected disparate equations of movement of the separated framework in the gradual form are solved iteratively. The response of the framework with bi-trend interaction is studied with those without interaction. as well, the influence of velocity based on the response of the separated framework are within scrutinized. furthermore, a parametric study is carried out to critically examine the influence of significant parameters on bi-trend interaction influences of the frictional forces of the VFPI. These parameters are: the STP, (FVF) and friction coefficient of the VFPI. of the above realization, it is showed that the base on of the friction coefficient on proportional velocity of the system does not have a noticeable effect on the peak response of the framework separated with VFPI, and that the bi-trends interaction of frictional forces of the VFPI is significant and if ignored separated displacements will be underestimated and the superstructure acceleration and base shear will beoverrate.

Nikolay et al. (2008) model led the notion of base isolation systems and check the decrease in lateral response becouse to a earthquake incident. The variance in responses were measured via study two congruous sample buildings, one with a FPS isolation device and one without FPS. And than wide testing on a Shake Table, the building with the FPS appeared a big reduction in lateral acceleration becouse to changing lateral forces, as predict. The greatest lateral acceleration spotted for the buildings with FPS was 0.23g which was lower than semi of the non-base isolated buildings that experienced a utmost lateral acceleration of 0.57g. The studied damping of all building appeared a identical direction with the building with FPS has a damping of 0.085 which were much than 5 times big than the building without FPS with a damping of 0.016. Generally the FPS appeared a big advancement in dynamic response of the sample building via decrease the lateral acceleration and rising the damping of the system.

Krishnamoorthy and Anita (2016) showed us finite element procedure to analyze the structure isolated with FPS considering the soil structure interaction. moreover, a numerical study is as well as took out in order to know the significance of considering soil structure interaction in the analysis of building isolated with FPS and to discuss the impact of various factors affecting soil structure interaction analysis. The results were as follows:

- Soil structure interaction impact on FPS isolated structure is affected significantly via the type of earthquake. For the present study it is showed that soil structure interaction effects are injurious for near-fault (NF) earthquakes whereas it is generally beneficial for far-field (FF) earthquakes.
- The soil structure interaction impact is also affected via the frequency content of earthquake ground motion. It is showed from this study that the low frequency earthquake ground motions may made injurious effects, whereas, beneficial effect due to soil structure interaction may be expected for high frequency ground motions.
- Injurious effect on story shear reduces as the story height increases and soil structure interaction may appear both beneficial and injurious effect on shear at various floors for the identical structure consequent to similar seisimic earth movement.
- The soil structure interaction effect as well based on the friction coefficient of FPS. At big friction coefficient the echo of isolated structure is similar to the echo of non isolated structure and therefore the soil structure interaction effect is either small or mostly beneficial whereas soil structure interaction appears injurious effect at small values of friction coefficient. One of the most noticeable It can be drawn of this study is that soil building interaction has negligible impact on base shear at optimum friction coefficient.
- Soil building interaction impact are also influenced via the isolation period of FPS. soil structure interaction may appear either negligible or beneficial impact

at small isolation periods while it may appear injurious impact at large values of isolation period, i.e. the injurious impact is larger for PF system compared to FPS system.

- It is as well observed that, if various structures have different floors but identical sizes of members and similar mass on each floor, then the impact of soil structure interaction is big for the structure with less number of floors and the impact decreases as the number of floors of structure increases. This is due to the increase in variation between the fundamental time period of the structures with and without interaction soil building as is the number of floor decreases. For the identical reason above, the impact of soil structure interaction also increases as the basic time period of the fixed base building decreases.
- Residual displacement is not influenced much due to soil building interaction and the soil building interaction impact on base shear and sliding displacement is observed once the structure starts sliding.
- The soil building interaction impacts the response of building significantly, it is significant to investigate the soil building interaction impacts in the analysis of structure isolated with FPS for purpose get the real response of structure isolated with FPS.

CHAPTER 3

METHODOLOGY

3.1 General

In this study, firstly, steel building with the fixed base system was designed for five storeys. Then, they were assessed to show the nonlinear behavior and performance state. After that, the steel building were modfied by adding friction pendulum isolation system with different coefficients of friction (0.06, 0.09, 0.111, and 0.18). Finally, nonlinear time history analysis was performed to evaluate the seismic behavior of the structure with the fixed base and friction pendulum isolation systems.

3.2 Analytical model of the structures

The proposed retrofitting methods were applied to five storey steel structure buildings that modified from the models studied by adding friction pendulum isolation system with different coefficients of friction (0.06, 0.09, 0.111, and 0.18). They were designed in accordance with the provisions FEMA-356 for gravity loads only. The models had the similar height of 3 m at each storey with five bays in X-direction and 3 bays Y-direction of 5 m, slab sections of 0.2 m width concrete slab. All the steel elements have the same cross section and material properties. Moreover, the design live load was taken to be equal to 5 kN/m^2, dead load 1.5 kN/m^2, wall 10 kN/m^2, roof live 1.5 kN/m^2, snow 1.25 kN/m^2 and finishing 1 kN/m^2. Load case formula DL + 0.3 LL was taken. The typical plan of the steel structure with a fixed base system (original building) for five storeys in Figure 3.1. The elevation and 3-dimensional views of the steel structure with a fixed base system and steel structure with a friction pendulum isolation system of five storeys are shown in Figures 3.2 and 3.3, respectively.

To upgrade the seismic performance of the five storey steel structure the friction pendulum isolation system was utilized. These friction pendulum isolation systems having different coefficient of friction was applied to increase effectiveness of damping in buildings by using the coefficient of friction of 0.06, 0.09, 0.111, and 0.18.

Thus, 5 different steel structure models (one of them as the origional steel structure with fixed base system and the rest of them as upgraded steel structures with friction pendulum isolation system) were investigated by performing nonlinear analysis.

Model parameters for friction pendulum isolation systems under earthquakes (Pomona, Yermo, Corralitos) were given below. Using the equations below according to ASCE 7-10 (2010), we obtained the parameters as shown in Tables 3.1-3.3. Where T_{eff} is effective period obtained from Eqn. (3.2), β_D is effective damping obtained from Eqn. (3.3) and K_{eff} is effective stiffness obtained from Eqn. (3.4), where values vary depending on the type of earthquake, the coefficient of friction for each case and the design displacement of the structure as a result of exposure to an earthquakes above.

$$Q_d = \mu . \sum W \tag{3.1}$$

Where Q_d is Effective stiffness, μ is the Friction coefficient and W is the structure's weight.

$$T_{eff} = 2\pi \sqrt{\frac{\sum W}{(K_{eff})(g)}} \tag{3.2}$$

$$\beta_D = \frac{4\mu \sum (D_D - D_y)}{2\pi K_{eff} D_D} \tag{3.3}$$

Where Dy is the initial displacement when moving off from the rest point and D_D is the design displacement.

$$K_{eff} = \frac{w}{R} + \frac{\mu w}{D_D} \tag{3.4}$$

Where R is the radius of the curvature.

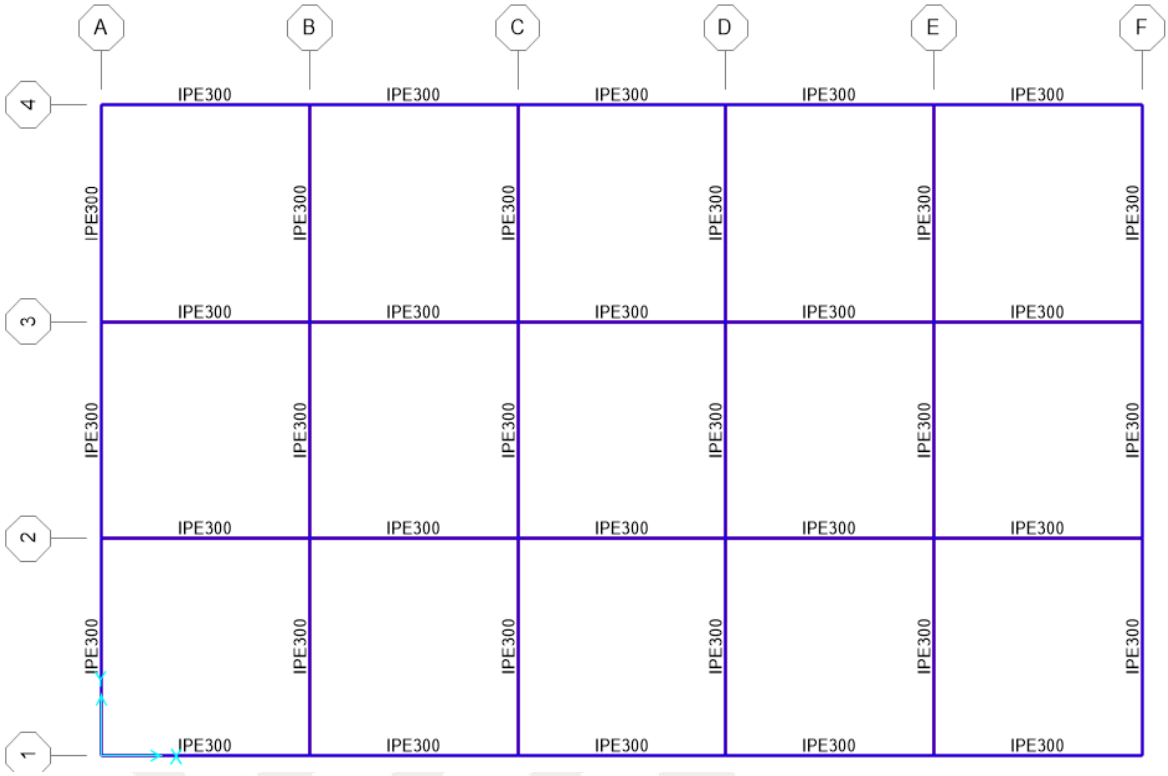
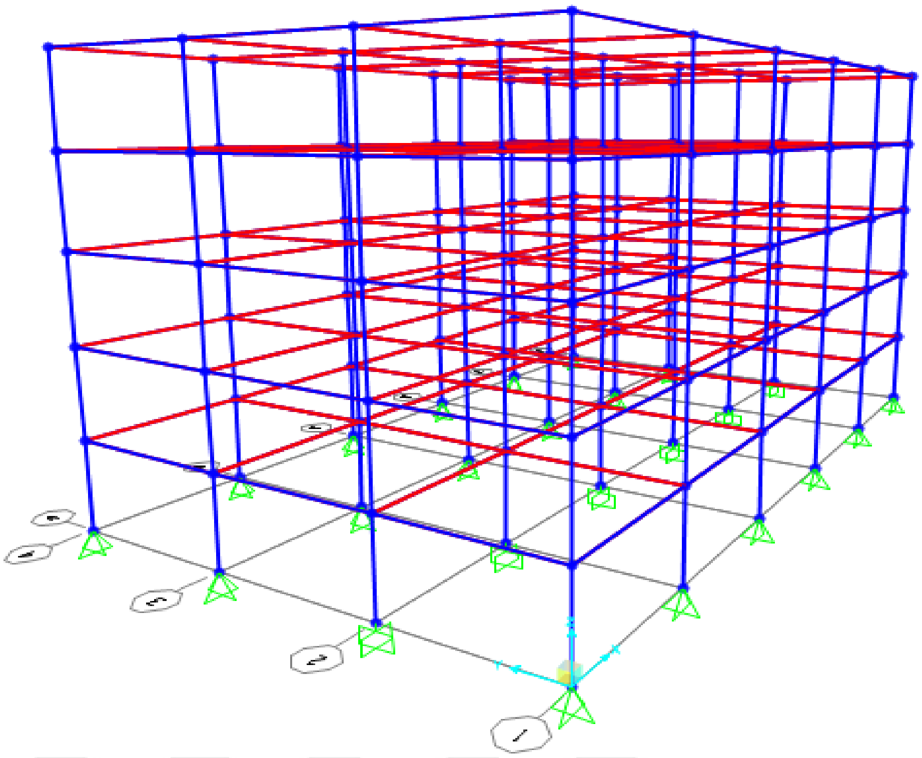


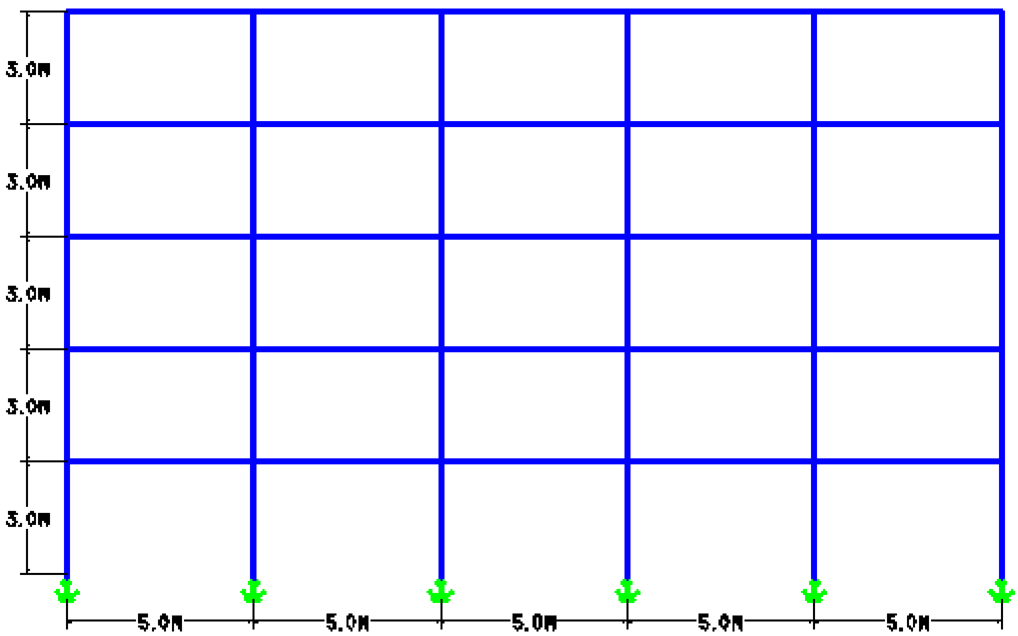
Figure 3.1 Plan view of the steel building

a)

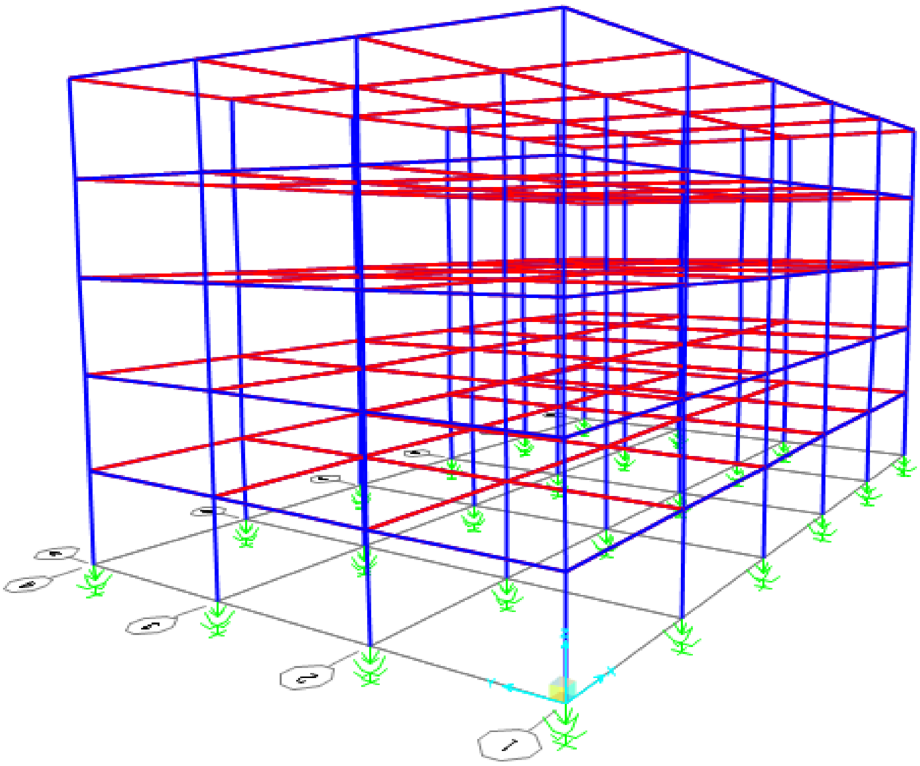


b)

Figure 3.2 (a) Elevation and (b) 3-dimensional views of the 5 storey steel structure with fixed base



a)



b)

Figure 3.3 (a) Elevation and (b) 3-dimensional views of the 5 storey steel structure with friction pendulum isolation system

Table 3.1 Parameters of FPS considering in Pomona earthquake

Type of models	Effective period T_{eff}	Effective stiffness (Keff)	Effective damping (β)	Friction coefficient (μ)	Radius (R)
Model 1	3.24	100.6	0.493	0.060	2.133
Model 2	2.75	120.0	0.533	0.090	2.133
Model 3	2.22	133.3	0.563	0.111	2.133
Model 4	2.02	178.0	0.579	0.180	2.133

Table 3.2 Parameters of FPS considering in Yermo earthquake

Type of models	Effective period T_{eff}	Effective stiffness (Keff)	Effective damping (β)	Friction coefficient (μ)	Radius (R)
Model 1	5.02	78.5	0.481	0.060	2.133
Model 2	4.24	86.8	0.514	0.090	2.133
Model 3	3.88	92.6	0.531	0.111	2.133
Model 4	3.10	111.7	0.553	0.180	2.133

Table 3.3 Parameters of FPS considering in Corralitos earthquake

Type of models	Effective period T_{eff}	Effective stiffness (Keff)	Effective damping (β)	Friction coefficient (μ)	Radius (R)
Model 1	5.79	74.4	0.489	0.060	2.133
Model 2	4.89	80.6	0.523	0.090	2.133
Model 3	4.47	85.0	0.540	0.111	2.133
Model 4	3.58	99.4	0.562	0.180	2.133

3.3 Non-linear time history analysis methods

Nonlinear dynamic analyses were carried out using the finite element program of SAP 2000 non-linear version 18 to determine the seismic performance of the five story steel building with the fixed base system and those with friction pendulum isolation system. For performing the time history analysis of building structure, the following steps are done:

1. Modeling of 5 storey fixed base structure and the other models with friction pendulum isolation were created and designed in SAP 2000.
2. Hinge properties were defined according to FEMA 356 (2000), and these properties are assigned at each end the beam and column members. For the column members, axial force and biaxial moment hinges (PMM) and for the beams, flexural moment hinges (M3) were considered.

So as to record for the variety of the building's reaction all through the span of every seismic tremor ground movement, a time history analysis was required. During performing the time history analysis, the building was subjected to three different ground motion records for (Pomona, Yermo and Corralitos earthquakes). Figures 3.4 - 3,6 show the acceleration-time plot of the above earthquakes. Hence, the response of the structures in terms of roof displacement versus time history, storey displacement, and inter-storey drift ratio were obtained.

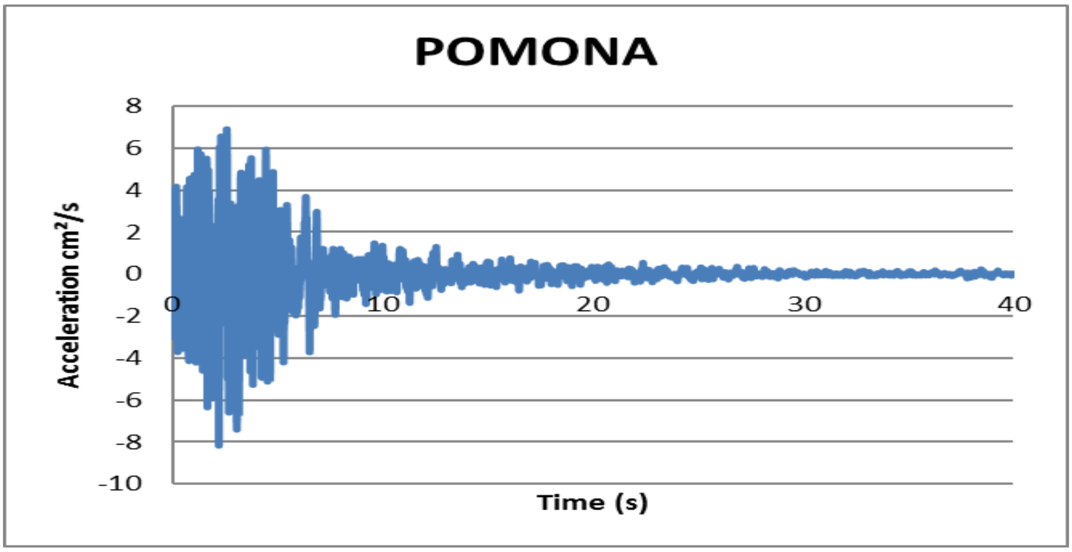


Figure 3.4 Acceleration time plot of the Pomona earthquake

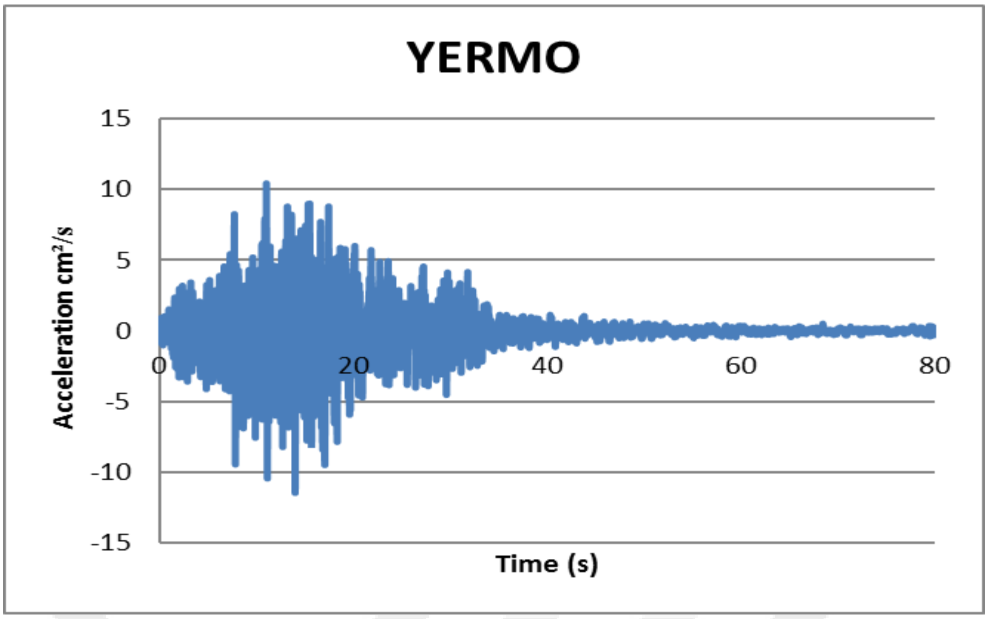


Figure 3.5 Acceleration time plot of the Yermo earthquake

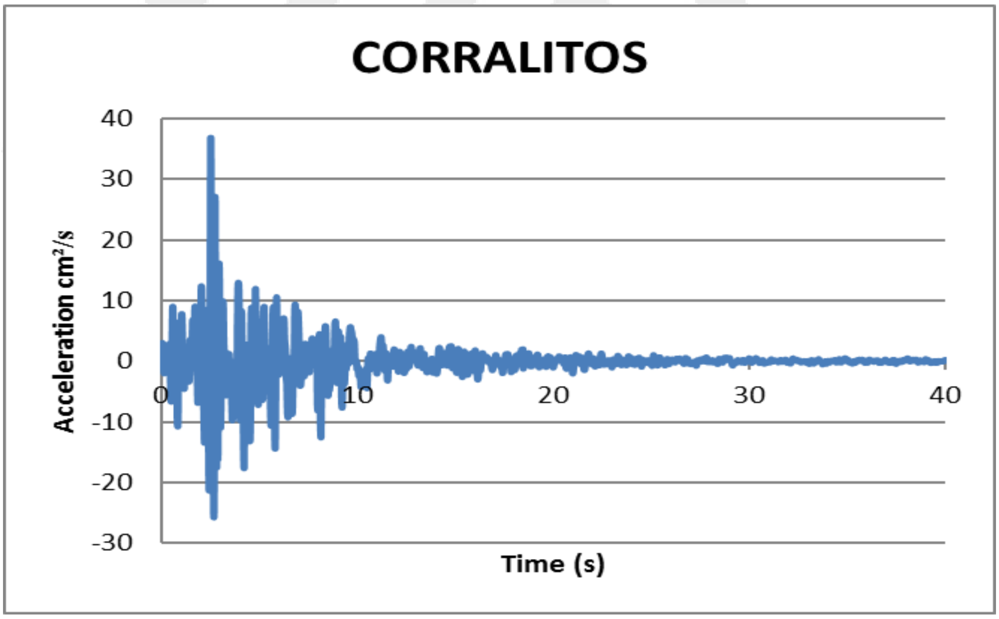


Figure 3.6 Acceleration time plot of the Corralitos earthquake

CHAPTER 4

RESULTS AND DISCUSSION

The analysis of the results of the fixed base building and that with friction pendulum isolation system were given in this chapter. The performance of the friction pendulum isolated structures designed with different friction coefficients having one radius of concave strategies was evaluated by using nonlinear time history analysis under three earthquakes. For this, a total of 5 different frame models were considered. One of them is as fixed base 5 stories and the rest of them are as isolated structures with friction pendulum isolation system with coefficients of friction of 0.06, 0.09, 0.111, and 0.18 for each one with a radius of concave 2.133 m. The results were obtained and discussed in terms of the maximum base shear vs. time history, roof displacement vs. time history, relative displacement vs. time history, story displacement, inter-story drift ratio, etc.

4.1 Analysis of results under Pomona earthquake

4.1.1 Variation of story relative displacement

Figure 4.1 shows the variation of story relative displacements of the 5 story fixed-base building and that with the friction pendulum isolation system having different friction coefficients of 0.06, 0.09, 0.111, and 0.18. As seen from the figure, the structures were subjected to pomona earthquake, it was observed that all structures under investigation were considerably affected by the given earthquake. Moreover, the use of friction pendulum isolation for the purpose of upgrading decreased remarkably the value of the maximum story displacements as compared to the fixed-base building, especially in the case of friction pendulum isolation system of 0.06 friction coefficient. The maximum story relative displacement was also affected by the number of stories and different coefficient of friction. For example, in the case of five story frame with a coefficient of friction 0.06, the maximum story relative displacement was smaller than other models with a higher friction coefficient or fixed base model.

According to the findings obtained from the nonlinear time history analysis, the friction coefficient of FPS was seemed to be very effective parameter in mitigating the earthquake response of the structure. Especially, the case of building with friction pendulum isolation systems with the lowest friction coefficient of 0.06 and then 0.09, 0.111 and 0.18, respectively, provided lower relative displacement and commonly less deformation than the fixed-base model under pomona earthquake. For example, as seen in Figure 4.1 for the five story building with fixed-base under the pomona earthquake, the maximum displacement of the existing frame was obtained as 19.31 cm while the maximum displacement of in the case of retrofitted with friction pendulum isolation systems with the lowest friction coefficient 0.06 and then 0.09, 0.111 and 0.18, respectively, obtained as 5.67 cm, 7.62 cm, 8.87 cm and 12.13 cm, respectively. As a result, it was appeared that the use of friction pendulum isolation systems with the lowest friction coefficient frames was better where decreased significantly the maximum displacement as compared with the building having the fixed - base support.

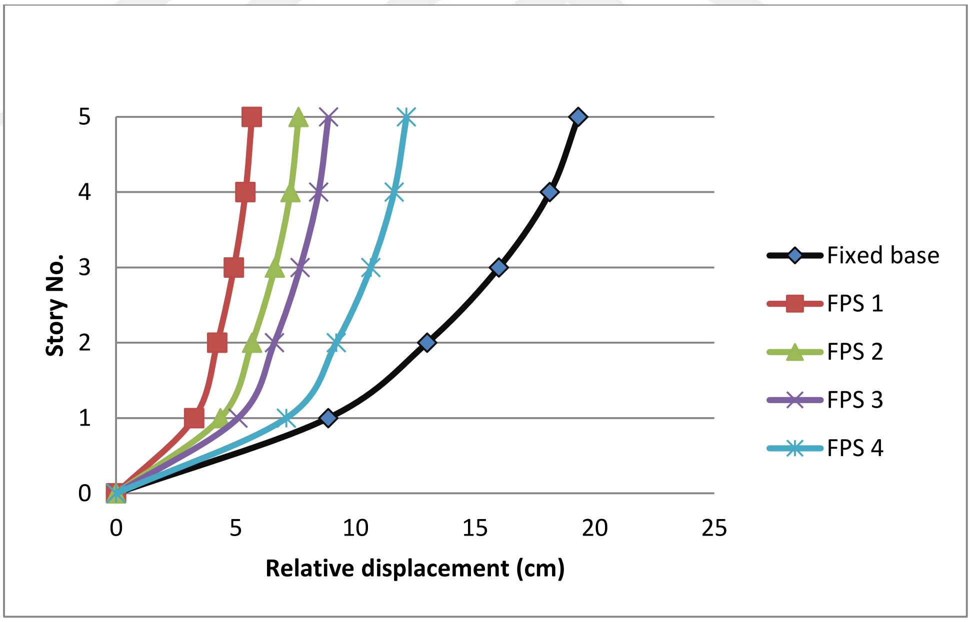


Figure 4.1 Relative displacement variation between fixed base system and FPS having different coefficients of friction

4.1.2 Variation of story relative drift

The plots for the relative drift of the fixed-base building and that upgraded by friction pendulum isolation considering different friction coefficients of 0.06, 0.09, 0.111, and 0.18 are given in Figures 4.2. According to the analysis of the results, using the friction pendulum isolation systems decreased significantly relative drift of the fixed-base system under the Pomona earthquake. For example, as seen in Figure 4.2, for the five story building, under the Pomona earthquake, the maximum relative drift of the fixed-base system was achieved as 8.85 cm while the maximum relative drift of a friction pendulum isolation system with different coefficients of friction of 0.06, 0.09, 0.111 and 0.18 was obtained as 3.25 cm, 4.36 cm, 5.09 cm and 7.1 cm, respectively.

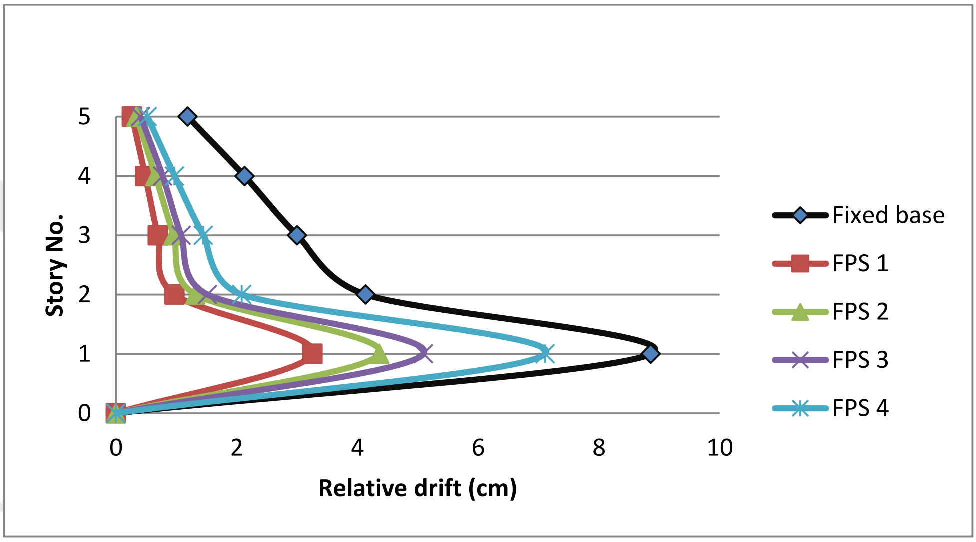


Figure 4.2 Relative drift variation between fixed base system and FPS

4.1.3 Inter-story drift ratio

The plots for the inter-story drift ratio of the fixed-base system and the friction pendulum isolation system are given in Figure 4.3. According to the analysis of the results, using the friction pendulum isolation systems decreased significantly inter-story drift ratio of the fixed-base system under the Pomona earthquake. For example, as seen in Figure 4.3, for the five story building, under the Pomona earthquake, the maximum inter-story drift ratio of the fixed-base system was achieved as 2.95%, while the maximum inter-story drift ratio of friction pendulum isolation systems with different coefficients of friction of 0.06, 0.09, 0.111 and 0.18 was obtained as 1.08, 1.45, 1.69 and 2.37%, respectively. The inter-story drift demands over the height of the fixed-base and the friction pendulum isolation systems were evaluated as seen in Figures 4.3. In general, it could be observed that the addition of friction pendulum isolation systems reduced significantly the drifts in the building. And this figure showed that the use of friction pendulum isolation system was better than the fixed-base system and in the case of frames with friction pendulum isolation system, the story drift demands were significantly lower.

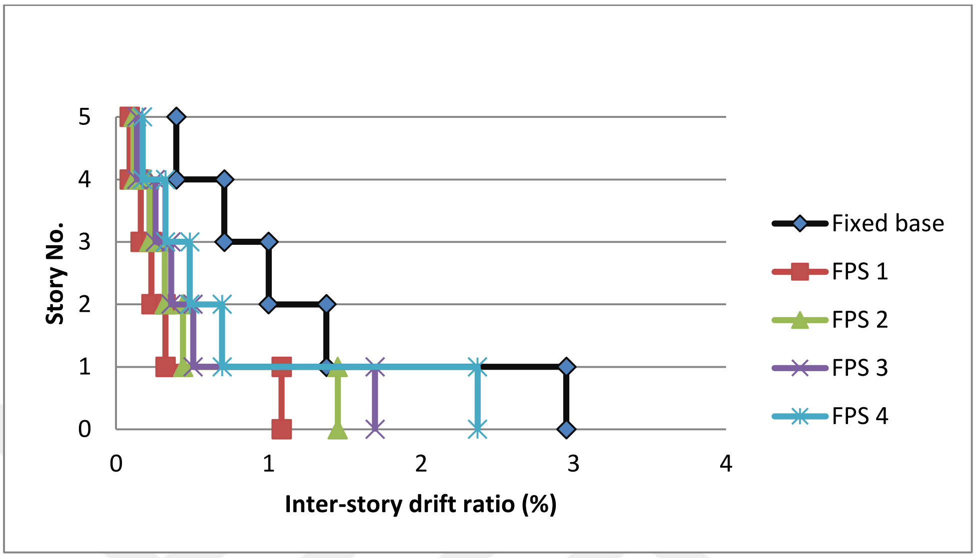
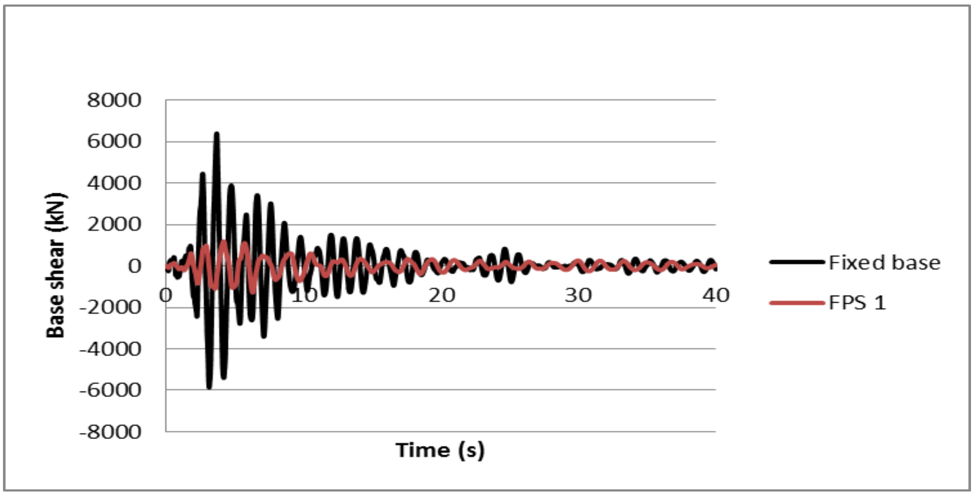


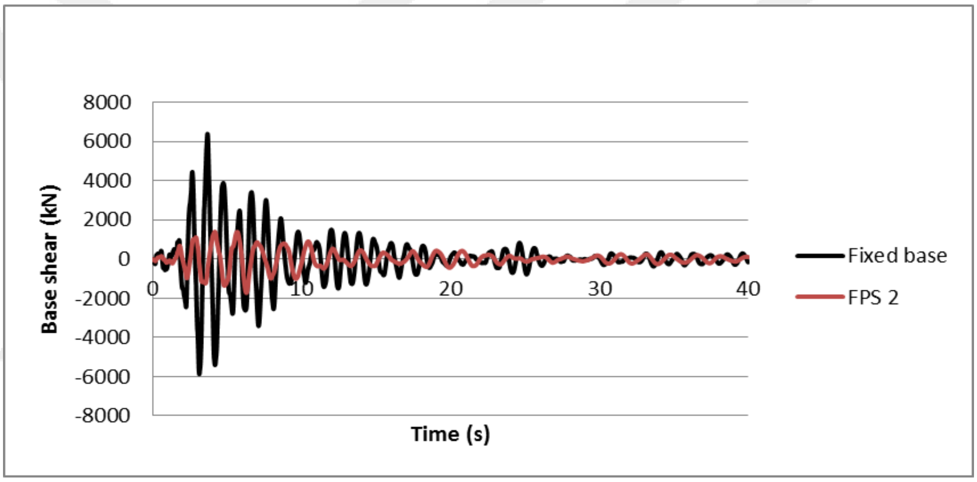
Figure 4.3 Variation inter-story drift ratio of fixed base system and FPS

4.1.4 Base shear time history

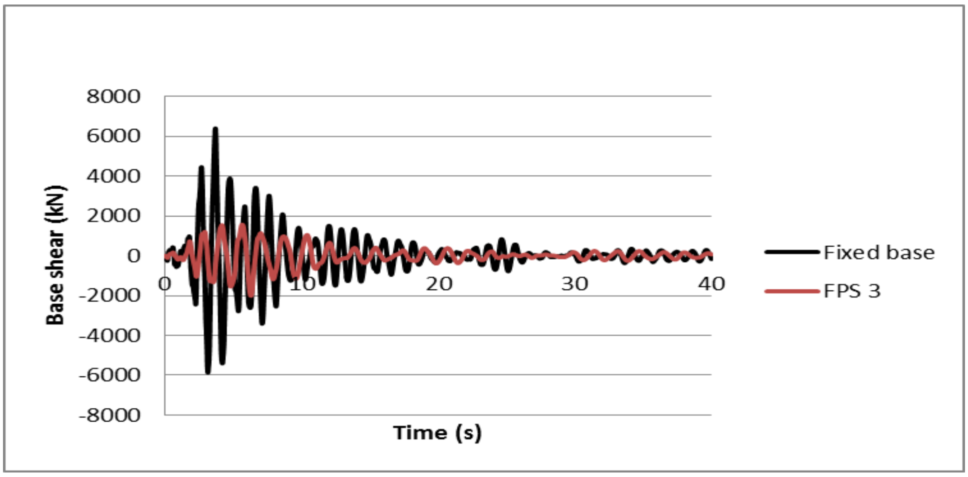
As a result of time history analysis, it was found that the FPS provided significant improvement in dynamic response of structure by reducing the base shear. For example, as shown in Figure 4.4, for the five story building under the Pomona earthquake, the maximum base shear of the fixed - base system was about 6046 kN while the maximum base shear of the friction pendulum isolation systems considering the different friction coefficients of 0.06, 0.09, 0.111, and 0.18 was achieved as approximately 593 kN, 866 kN, 1115 kN and 2109 kN, respectively. As seen from the figure, the results showed that the use of friction pendulum isolation system was better than of a fixed - base system, the maximum base shear demands were significantly smaller.


8000
6000
4000
2000
0
-2000
-4000
-6000
-8000
Base shear (kN)
0
10
20
30
40
Time (s)
Fixed base
FPS 1

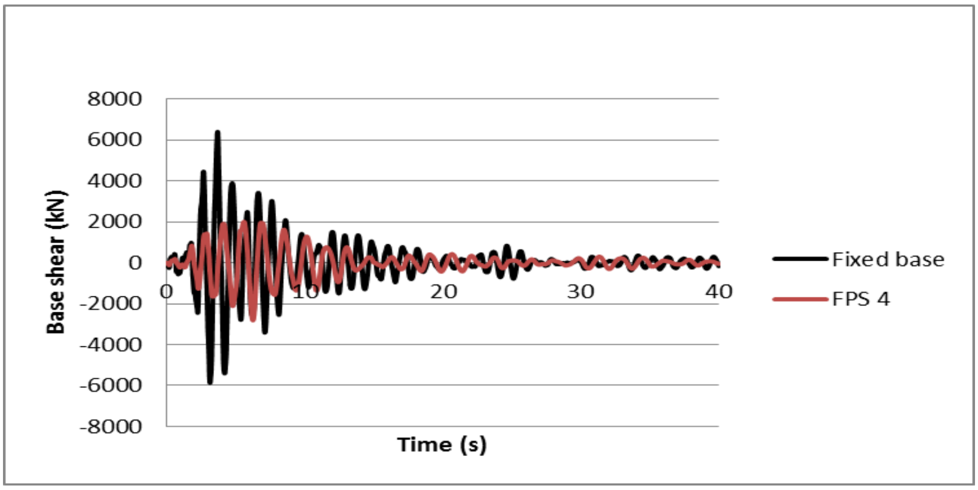
a)


8000
6000
4000
2000
0
-2000
-4000
-6000
-8000
Base shear (kN)
0
10
20
30
40
Time (s)
Fixed base
FPS 2

b)


8000
6000
4000
2000
0
-2000
-4000
-6000
-8000
Base shear (kN)
0
10
20
30
40
Time (s)
Fixed base
FPS 3

c)



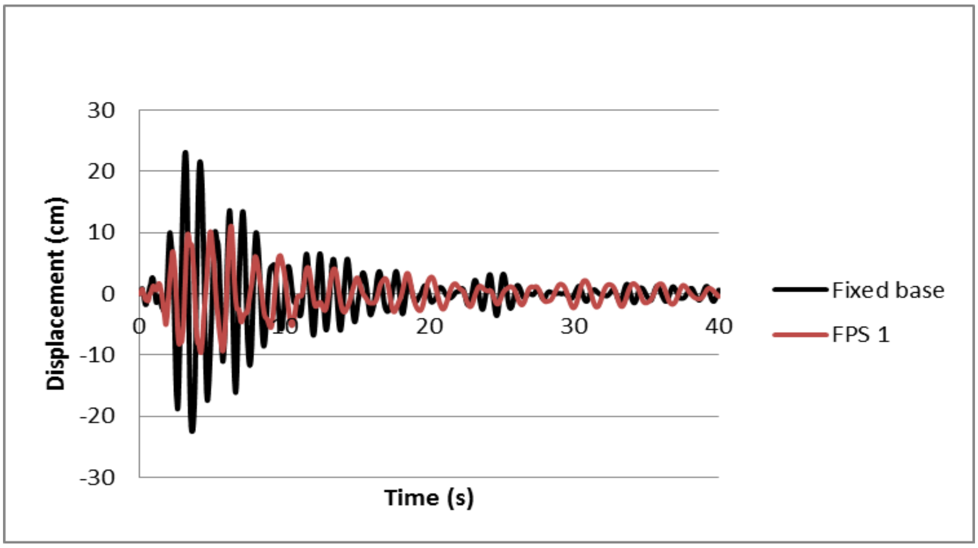
d)

Figure 4.4 Base shear time history of fixed base system and FPS with coefficient of friction of a) 0.06, b) 0.09, c) 0.111, and d) 0.18

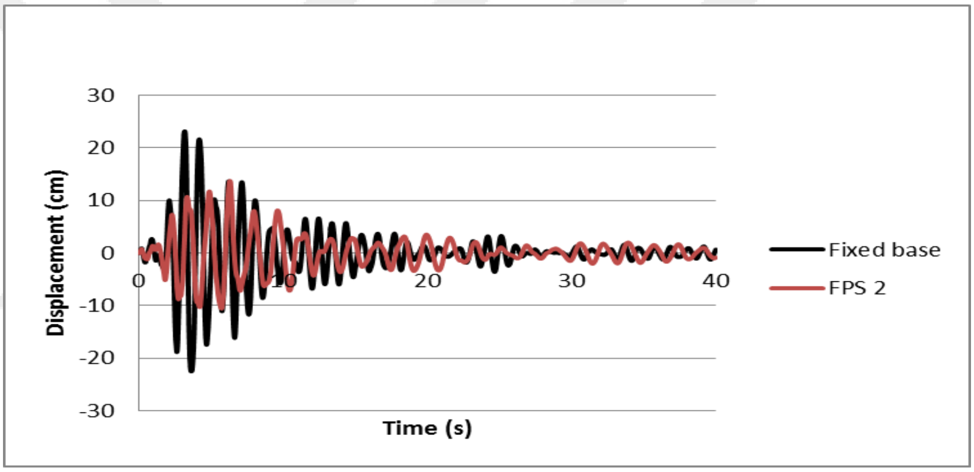
4.1.5 Roof displacement time history

Figure 4.5 shows the time history of the roof displacement of the fixed-base building and friction pendulum isolated building with different coefficients of friction of 0.06, 0.09, 0.111, and 0.18 under the Pomona earthquake. The use of the friction pendulum isolation system in the building remarkably decreased the value of roof displacement compared to the fixed-base system, especially in the case of frames with a friction pendulum isolation system with the lowest friction coefficient of 0.06 and then 0.09, 0.111 and 0.18, respectively.

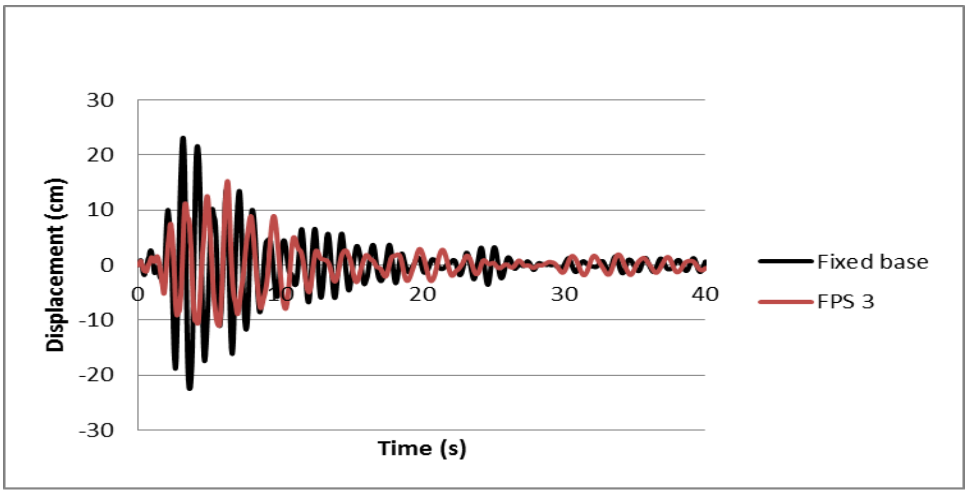
For example, as shown in Figure 4.5, for the five story building under the Pomona earthquake, the maximum roof displacement of the fixed base system was about 21.7 cm while the maximum roof displacement of the friction pendulum isolation systems with friction coefficients of 0.06, 0.09, 0.111, and 0.18 was achieved as approximately 9.48 cm, 12.23 cm, 13.39 cm and 17.03 cm, respectively. Therefore, it could be observed generally that the addition of friction pendulum isolation systems reduced significantly the drifts in the structures.


Displacement (cm)
30
20
10
0
-10
-20
-30
0
10
20
30
40
Time (s)
Fixed base
FPS 1

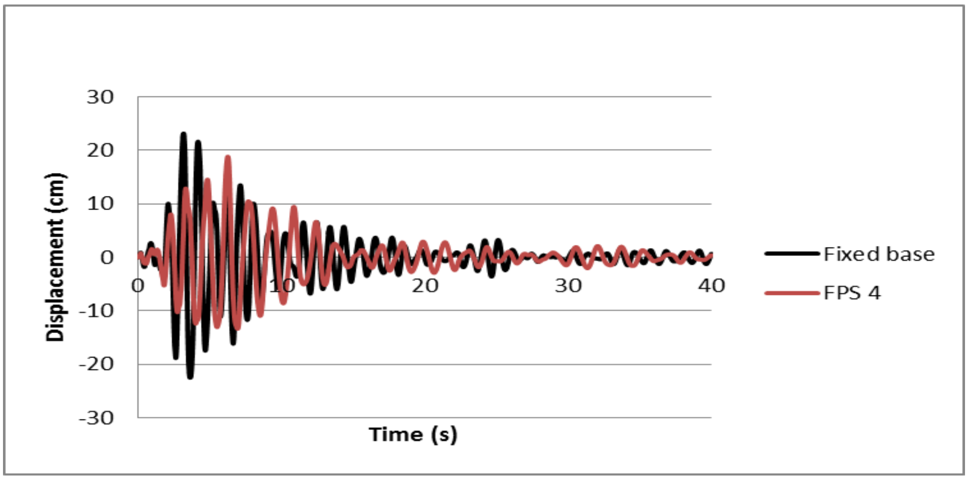
a)


Displacement (cm)
30
20
10
0
-10
-20
-30
0
10
20
30
40
Time (s)
Fixed base
FPS 2

b)


Displacement (cm)
30
20
10
0
-10
-20
-30
0
10
20
30
40
Time (s)
Fixed base
FPS 3

c)

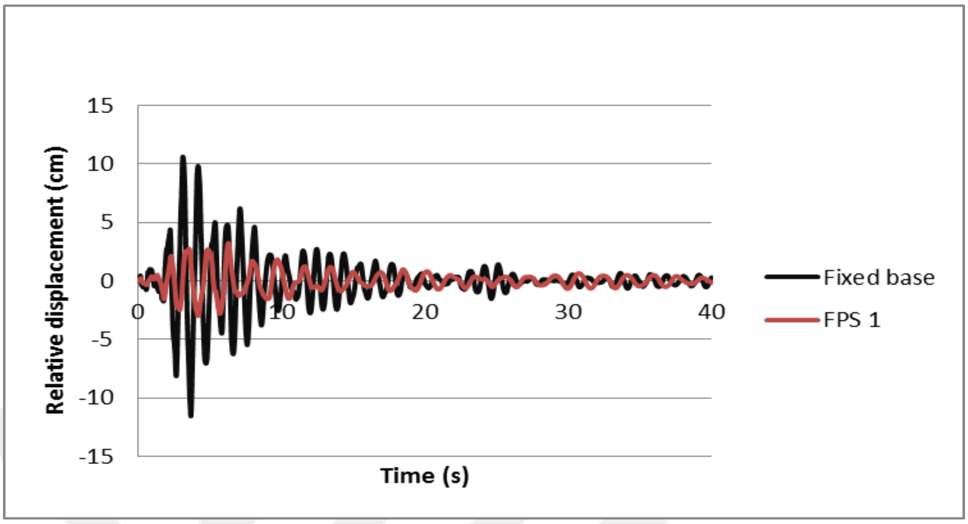


d)

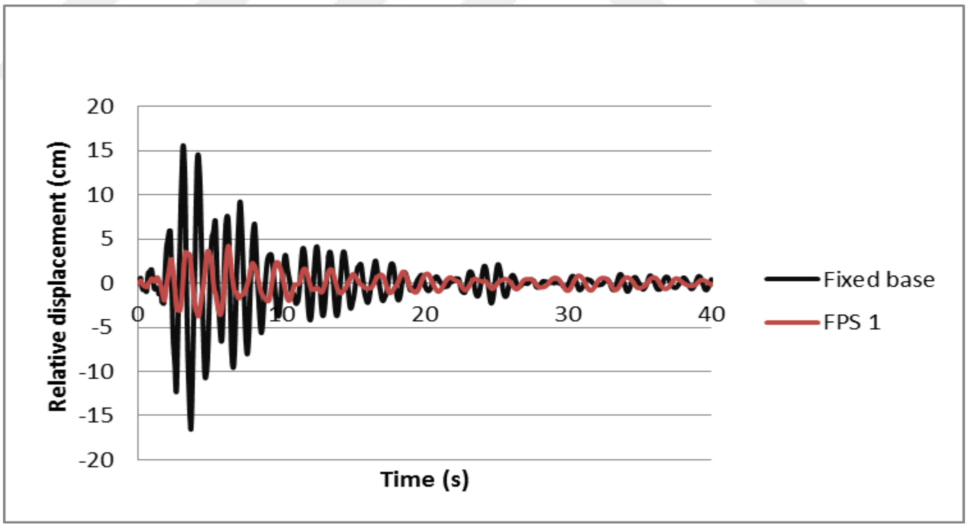
Figure 4.5 Displacement time history of fixed base system and FPS with coefficient of friction of a) 0.06, b) 0.09, c) 0.111, and d) 0.18

4.1.6 Relative displacement time history

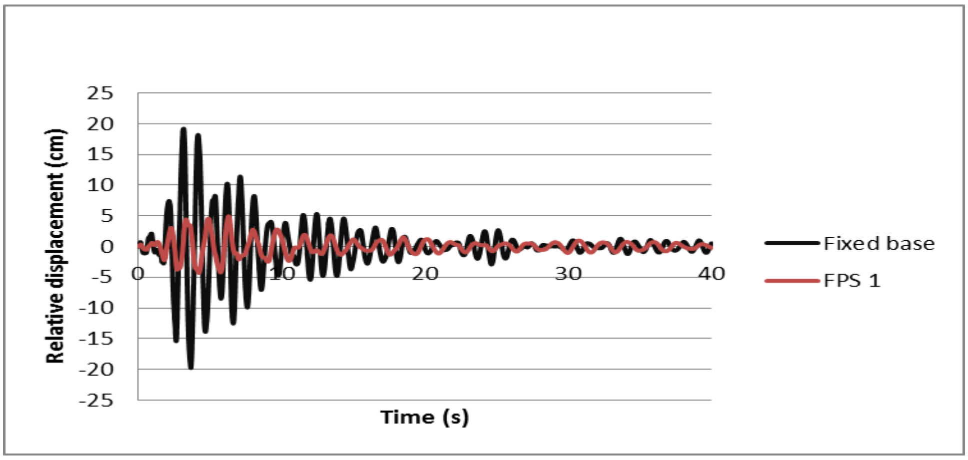
Figures 4.6 - 4.9 show the time history plots of the relative displacement for all floors of the building of the fixed-base system and friction pendulum isolation system under the Pomona earthquake. According to the results obtained from the nonlinear time history analysis, irrespective friction coefficient used, the friction pendulum isolation systems decreased significantly relative displacement of the existing building under the Pomona earthquake. For example, as shown in Figure 4.6, for the five story building under the Pomona earthquake the maximum relative displacement of the fixed base system was about 10.24 cm, 14.7 cm, 18.1 cm, 20.5 cm and 22.6 cm for each floor from 1 to 5, respectively, while the maximum relative displacement of the friction pendulum isolation systems considering the friction coefficient of 0.06 was achieved as approximately 2.4 cm, 3.1 cm, 3.9 cm, 5.1 cm and 5.6 cm respectively. In the case of 0.09 friction coefficient as shown in Figure 4.7, the relative displacement was as follows 4.1 cm, 5.6 cm, 6.6 cm, 7.3 cm and 7.6 cm for each floor from 1 to 5, respectively. As well as in Figures 4.8 and 4.9, a friction coefficient of 0.111 and 0.18 was used. It was observed that the relative displacement was as (5.1 cm, 6.6 cm, 7.7 cm, 8.5 cm and 9 cm) and (7.1 cm, 9.2 cm, 10.6 cm, 11.6 cm and 12.2 cm) over the height of the structure, respectively. Therefore, it could be observed generally that the addition of friction pendulum isolation systems reduced significantly the drifts in the frames. As seen from the figures, the results showed that the use of friction pendulum isolation system was better than that of the fixed -base system and in the case of frames with friction pendulum isolated systems, the maximum relative displacement demands were significantly smaller.



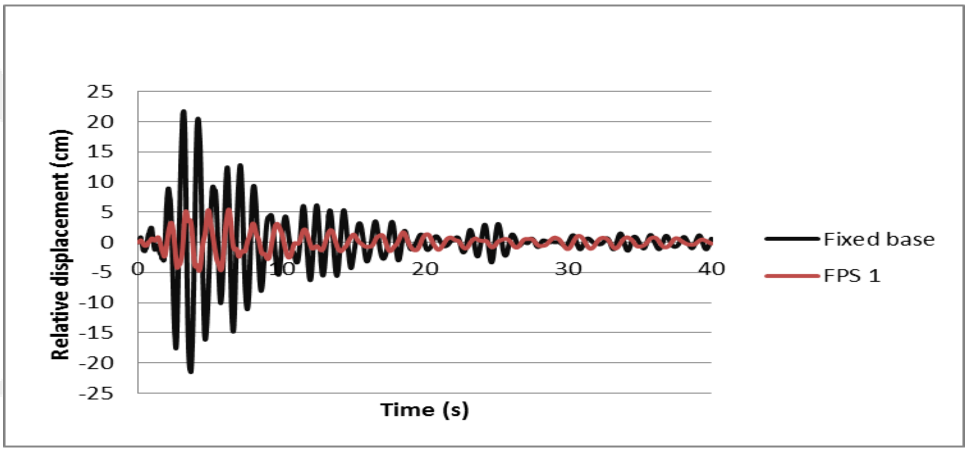
a)



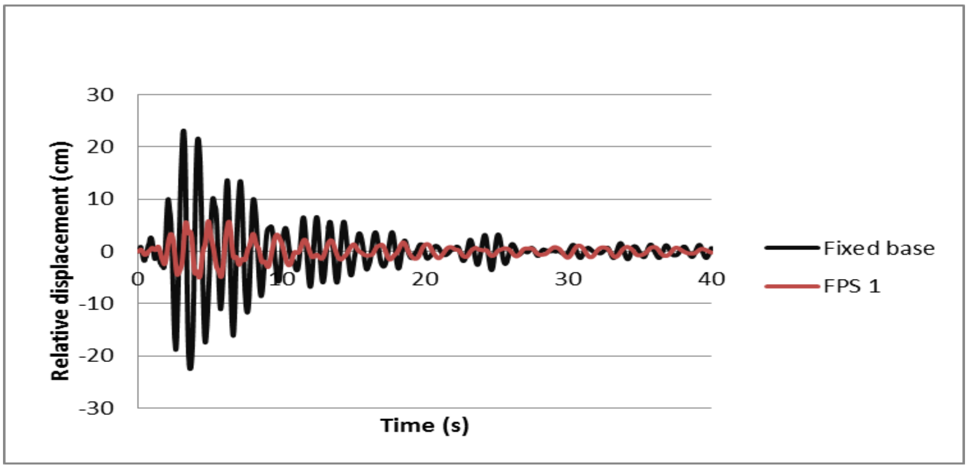
b)



c)

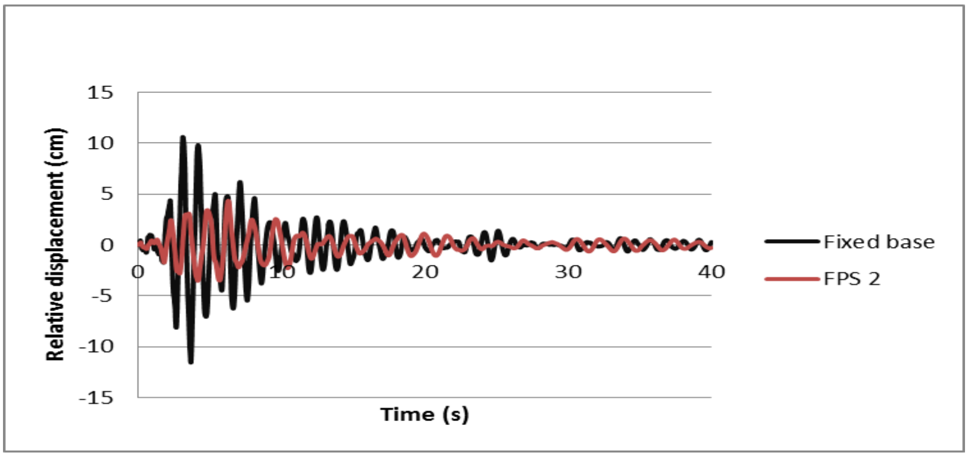


d)



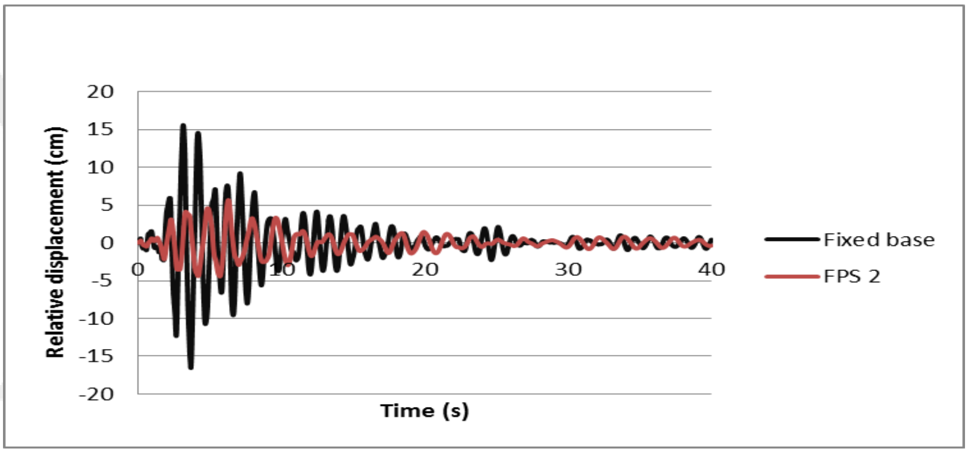
e)

Figure 4.6 Relative displacement vs. time for fixed base and FPS 1 cases at a) 1st, b) 2nd, c) 3rd, d) 4th, and e) 5th story levels



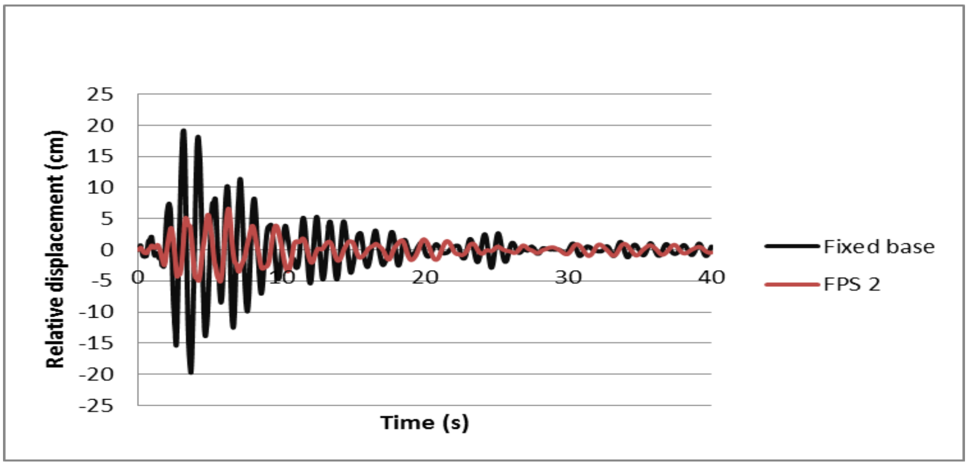
15
10
5
0
-5
-10
-15
Relative displacement (cm)
0
10
20
30
40
Time (s)
Fixed base
FPS 2

a)



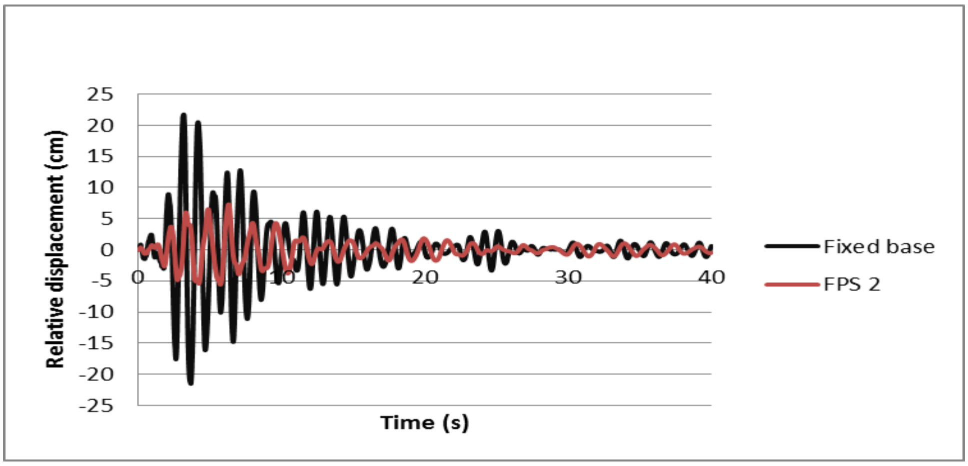
20
15
10
5
0
-5
-10
-15
-20
Relative displacement (cm)
0
10
20
30
40
Time (s)
Fixed base
FPS 2

b)

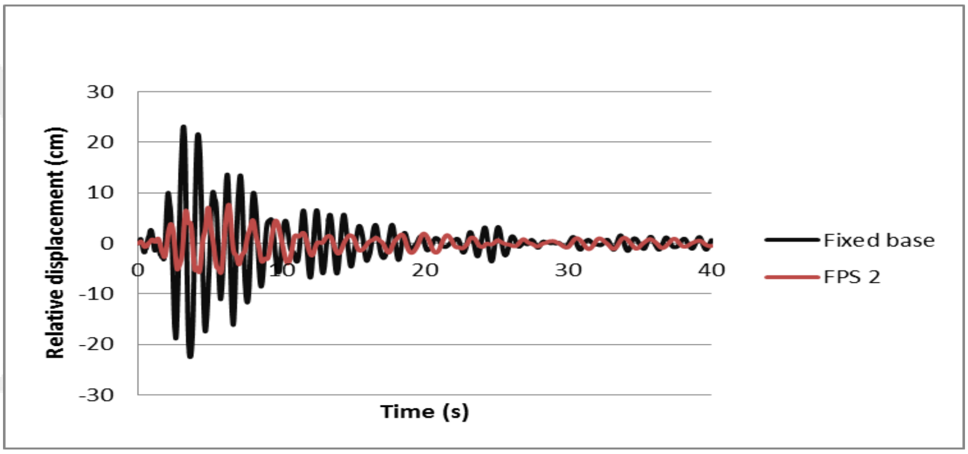


25
20
15
10
5
0
-5
-10
-15
-20
-25
Relative displacement (cm)
0
10
20
30
40
Time (s)
Fixed base
FPS 2

c)

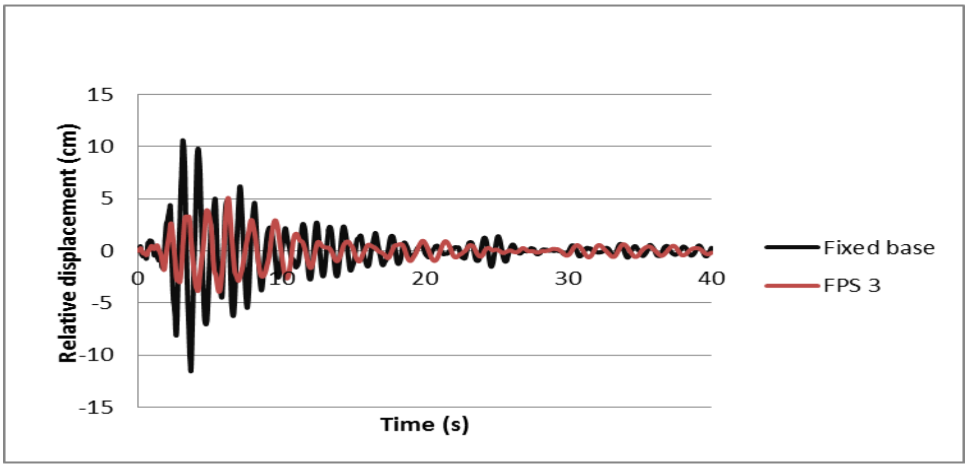


d)

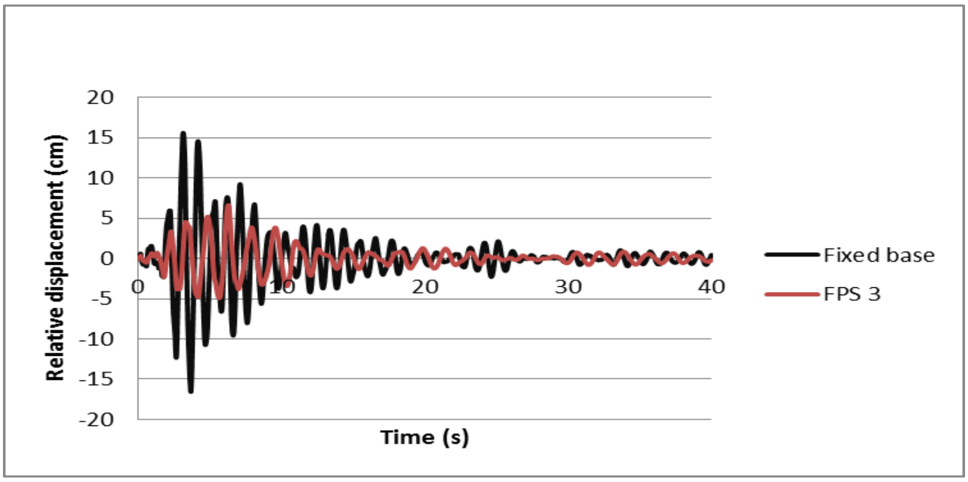


e)

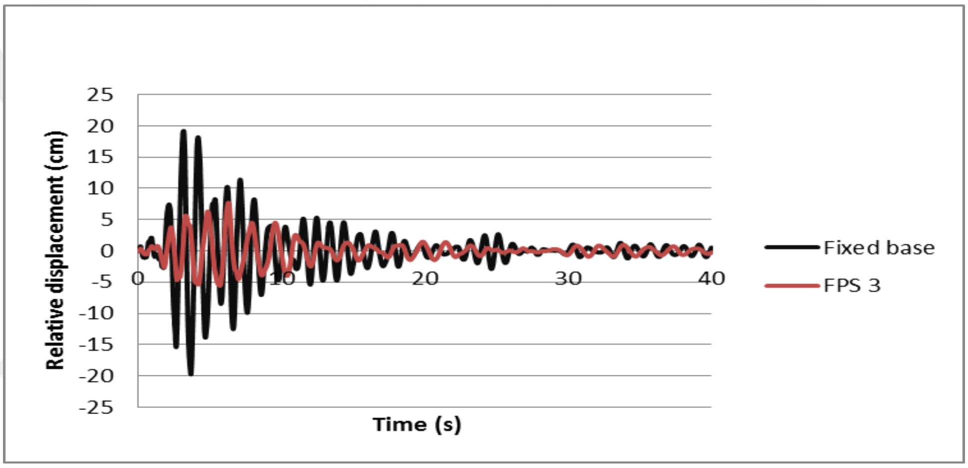
Figure 4.7 Relative displacement vs. time for fixed base and FPS 2 cases at a) 1st, b) 2nd, c) 3rd, d) 4th, and e) 5th story levels



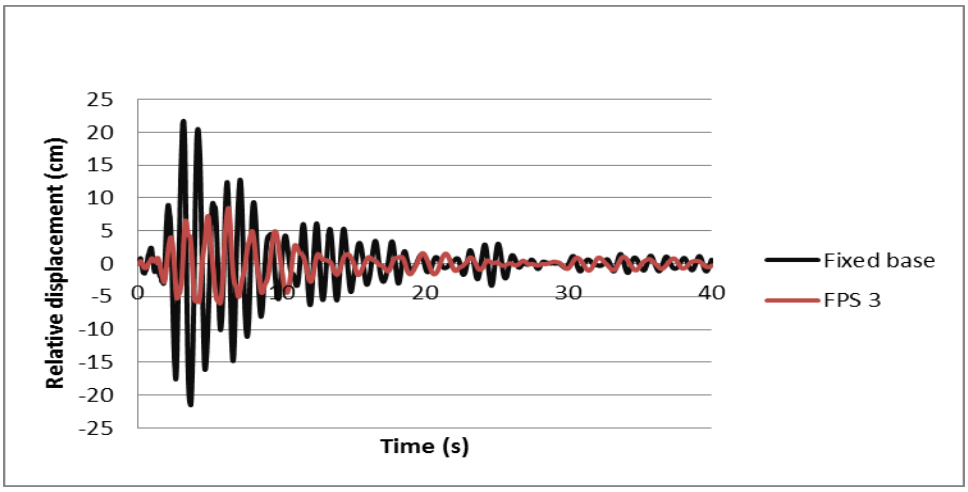
a)


20
15
10
5
0
-5
-10
-15
-20
Relative displacement (cm)
0
10
20
30
40
Time (s)
Fixed base
FPS 3

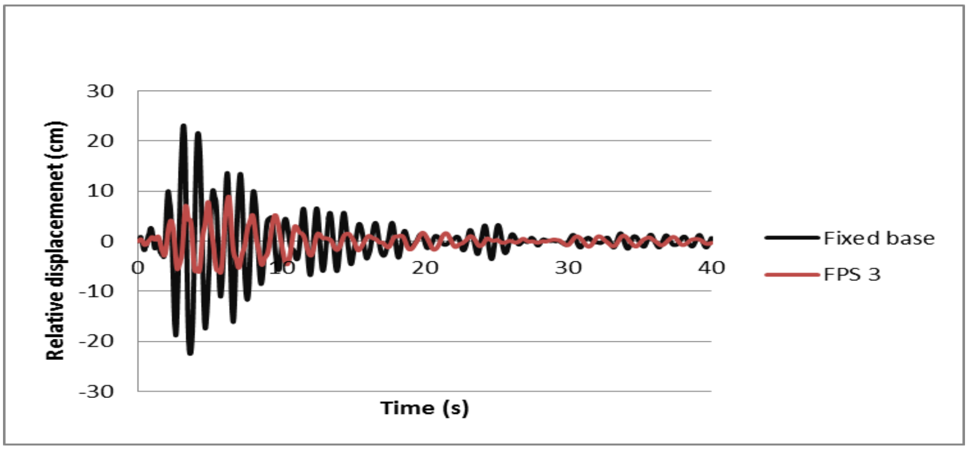
b)


25
20
15
10
5
0
-5
-10
-15
-20
-25
Relative displacement (cm)
0
10
20
30
40
Time (s)
Fixed base
FPS 3

c)

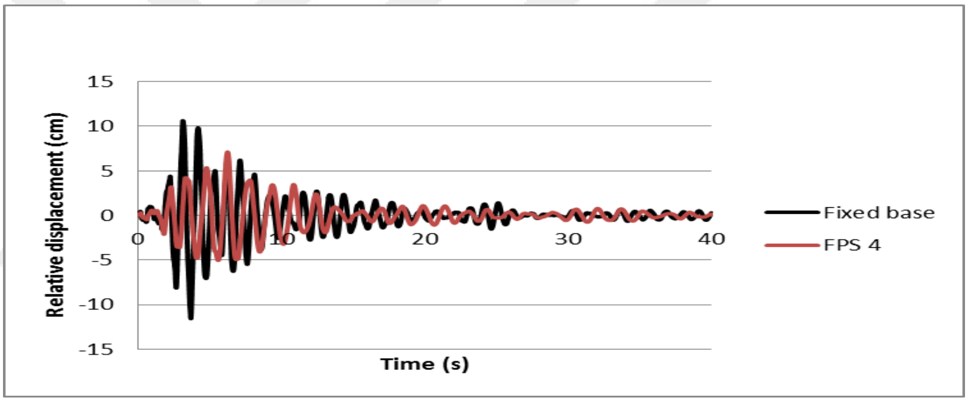

25
20
15
10
5
0
-5
-10
-15
-20
-25
Relative displacement (cm)
0
10
20
30
40
Time (s)
Fixed base
FPS 3

d)

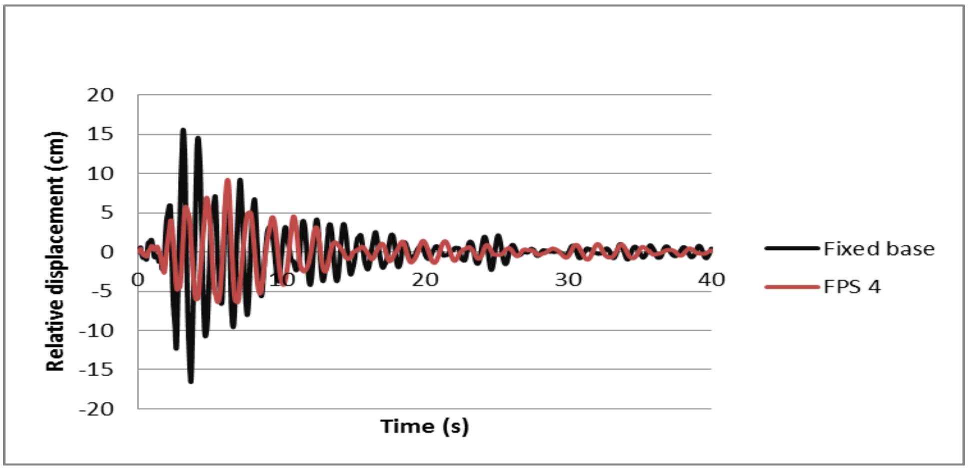


e)

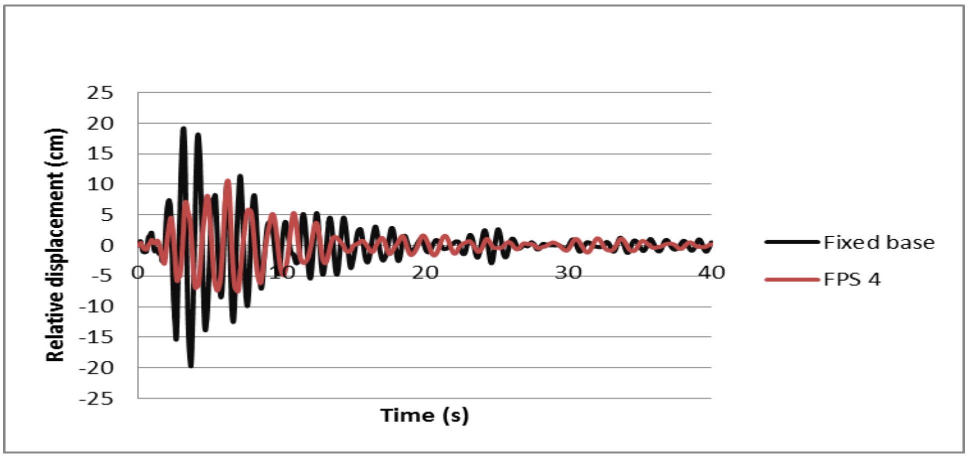
Figure 4.8 Relative displacement vs. time for fixed base and FPS 3 cases at a) 1st, b) 2nd, c) 3rd, d) 4th, and e) 5th story levels



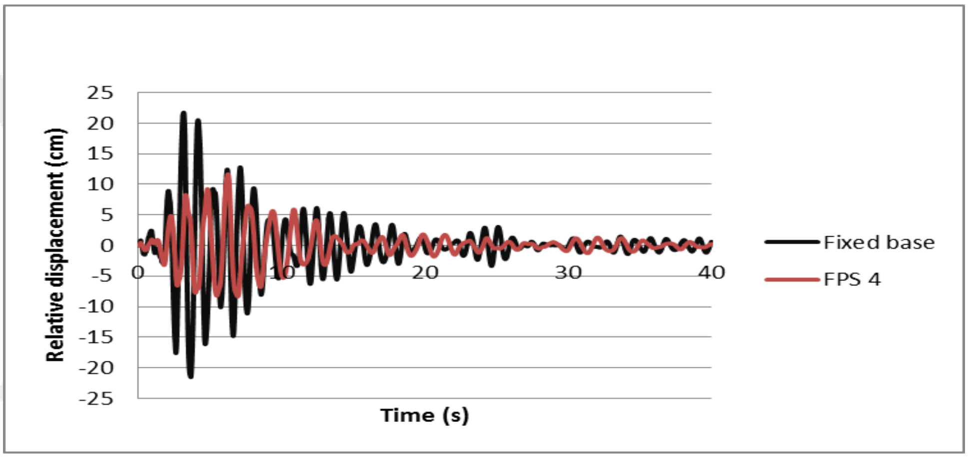
a)



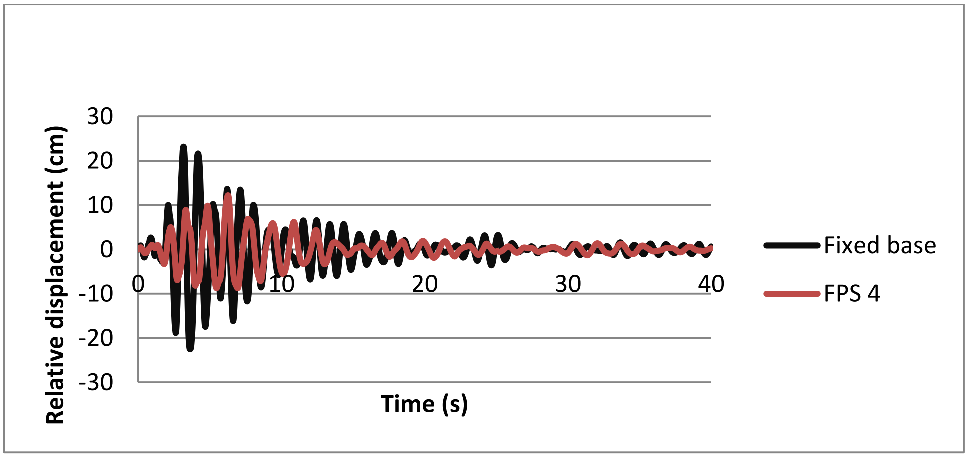
b)



c)



d)



e)

Figure 4.9 Relative displacement vs. time for fixed base and FPS 4 cases at a) 1st, b) 2nd, c) 3rd, d) 4th, and e) 5th story levels

4.1.7 Energy time history

The numerical analysis results given in Figures 4.10 and 4.11 showed that the input energy under the earthquake of Pomona for the structure with the fixed base system was remarkably high in comparison to that with friction pendulum isolation system.

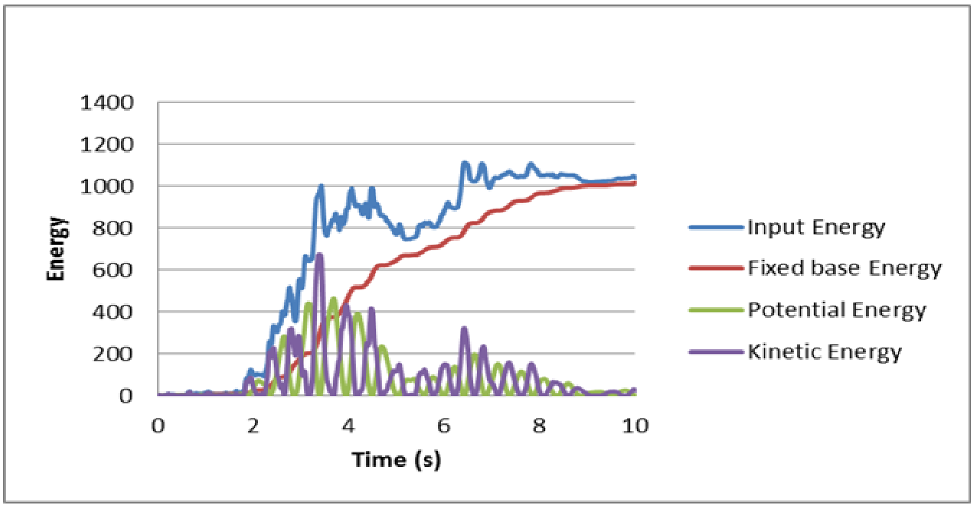
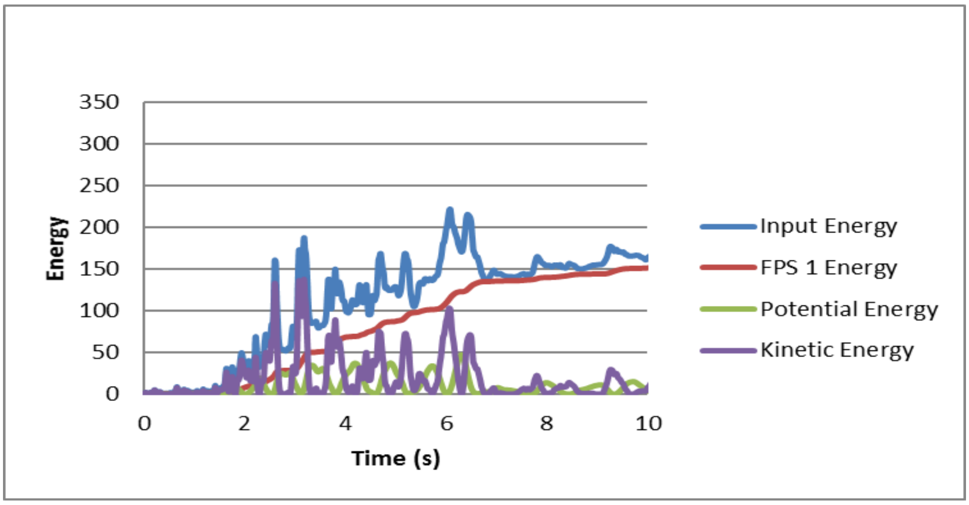
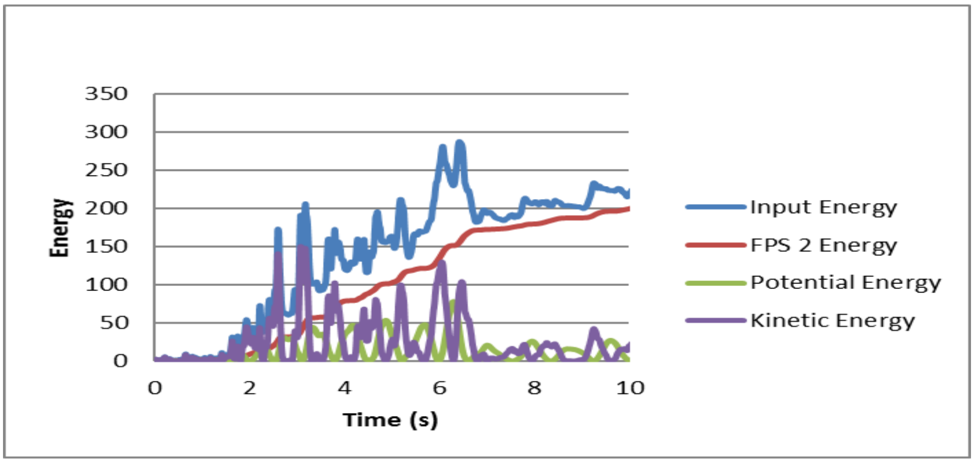


Figure 4.10 Energy within fixed base system under Pomona earthquake

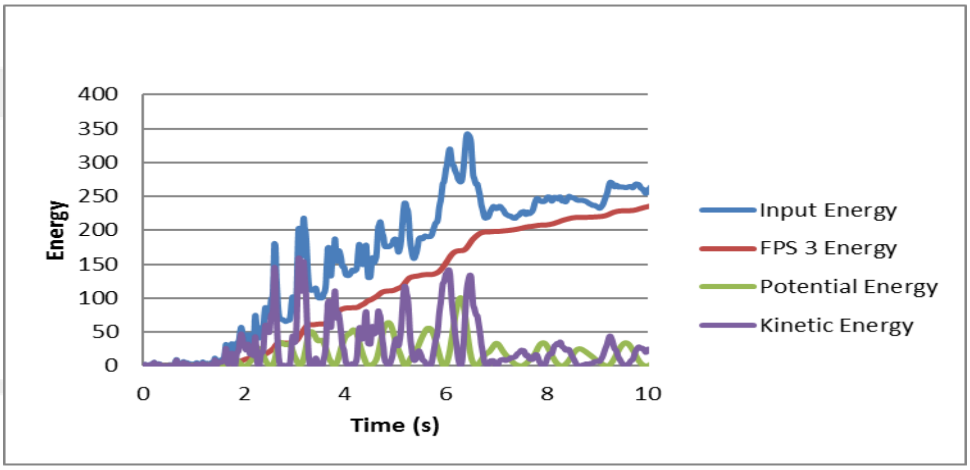
Efficiency of the friction pendulum system on the dissipation of the vibration energy was too high and kept the structure from the failure. Moreover, increasing the friction coefficient of FPS from 0.06 to 0.18 significantly increase the energy dissipated by the structure.



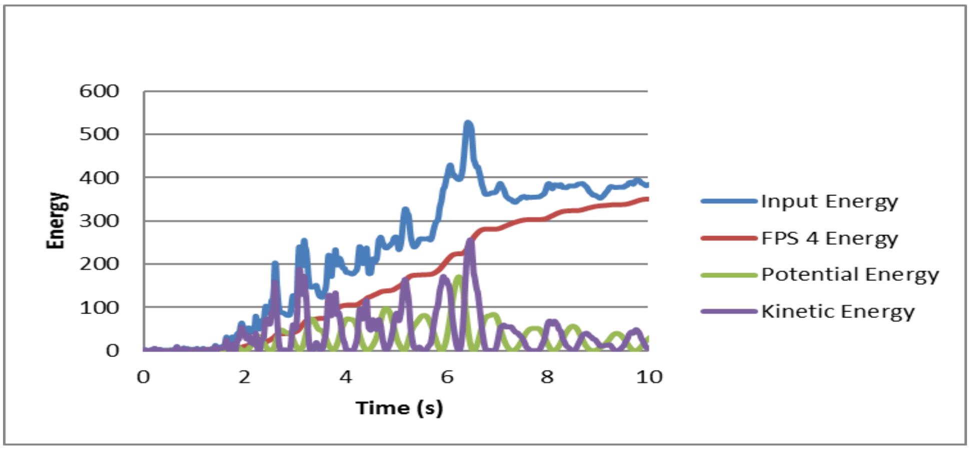
a)



b)



c)



d)

Figure 4.11 Energy within an isolated system under Pomona earthquake a) FPS 1, b) FPS 2, c) FPS 3 and d) FPS 4

4.2 Analysis of results under Yermo earthquake

4.2.1 Variation of story relative displacement

Figure 4.12 shows the variation of story relative displacements of the 5 story fixed-base building and that upgraded by friction pendulum isolation system, considering different friction coefficient 0.06, 0.09, 0.111, and 0.18 with a fixed radius of concave 2.133 m. As seen from the figure, all structures under investigation were considerably affected by the given earthquake. Moreover, the use of friction pendulum isolation for the purpose of upgrading strategies decreased remarkably the value of the maximum story relative displacements as compared to the fixed - base system.

According to the findings obtained from the nonlinear time history analysis, the maximum story relative displacement was also affected by the coefficient of friction. For example, in the case of five story building with a coefficient of friction 0.06, the maximum story relative displacement was smaller than the others with a higher friction coefficient or fixed-base model. When we checked the displacement values, it was observed that in the case of the five story building with fixed-base under Yermo earthquake, the maximum relative displacement was obtained as 47.66 cm while the maximum relative displacement of in the case of building with friction pendulum isolation systems with the lowest friction coefficient 0.06 and then 0.09, 0.111 and 0.18, respectively, obtained as 20.74 cm, 22.63 cm, 24.38 cm and 26.78 cm, respectively. As a result, it was clearly appeared that the use of friction pendulum isolation systems with the lowest friction coefficient frames was better where decreased significantly the maximum relative displacement compare of the original frames with fixed-base.

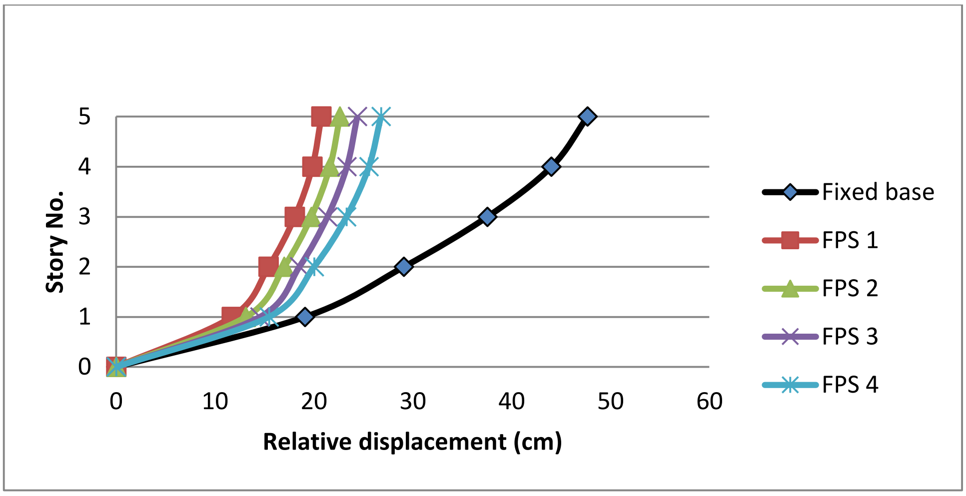


Figure 4.12 Relative displacement variation between fixed base system and FPS having different coefficients of friction

4.2.2 Variation of story relative drift

The plots for the relative drift of the buildings with the fixed-base system and friction pendulum isolation systems having different friction coefficients of 0.06, 0.09, 0.111, and 0.18 are given in Figures 4.13. According to the analysis of the results, using the friction pendulum isolation systems decreased significantly relative drift of the fixed-base system under Yermo earthquake. For example, as seen in Figure 4.13, for the five story building under Yermo earthquake, the maximum relative drift of the fixed-base system was achieved as 19.1 cm while the maximum relative drift of a friction pendulum isolation system with different coefficients of friction 0.06, 0.09, 0.111 and 0.18 was obtained as 11.6 cm, 13.1 cm, 14.5 cm and 15.4 cm, respectively.

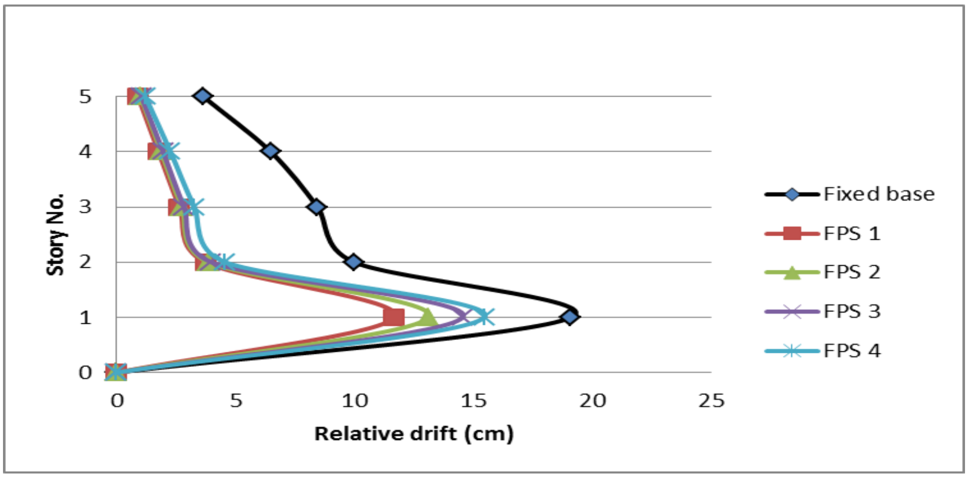


Figure 4.13 Relative drift variation between fixed base system and FPS

4.2.3 Inter-story drift ratio

The plots of the inter-story drift ratio of the structure with the fixed-base system and retrofitted by friction pendulum isolation system having different friction coefficients 0.06, 0.09, 0.111, and 0.18 are given in Figure 4.14. According to the analysis of the results, using the friction pendulum isolation systems decreased significantly the inter-story drift ratio of the building under Yermo earthquake. For example, as seen in Figure 4.14, for the five story building, under the Yermo earthquake, the maximum inter-story drift ratio of the fixed-base system was achieved as 6.36%, while the maximum inter-story drift ratio of friction pendulum isolation systems with different coefficients of friction 0.06, 0.09, 0.111 and 0.18 was obtained as 3.89, 4.37, 4,84 and 5.15%, respectively. In general, it could be observed that the addition of friction pendulum isolation systems reduced significantly the drifts in the building. And this figure showed that the use of friction pendulum isolation system was better than the fixed-base system and in the case of building with friction pendulum isolation system, the story drift demands were significantly lower.

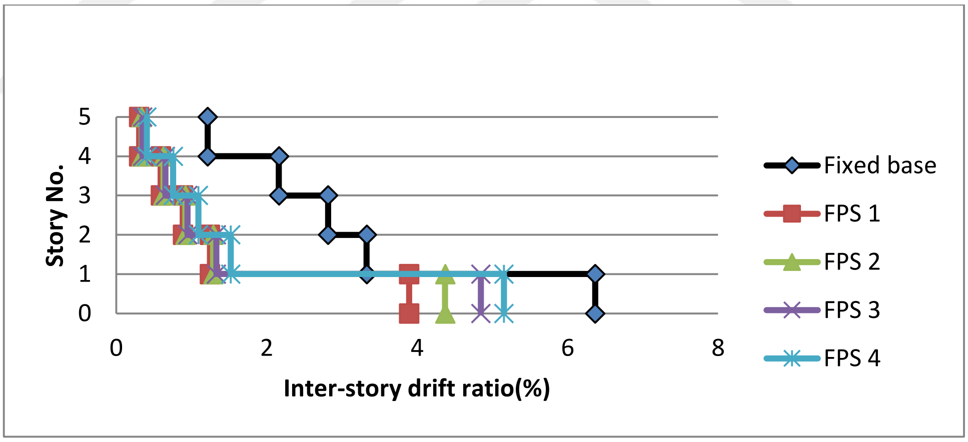
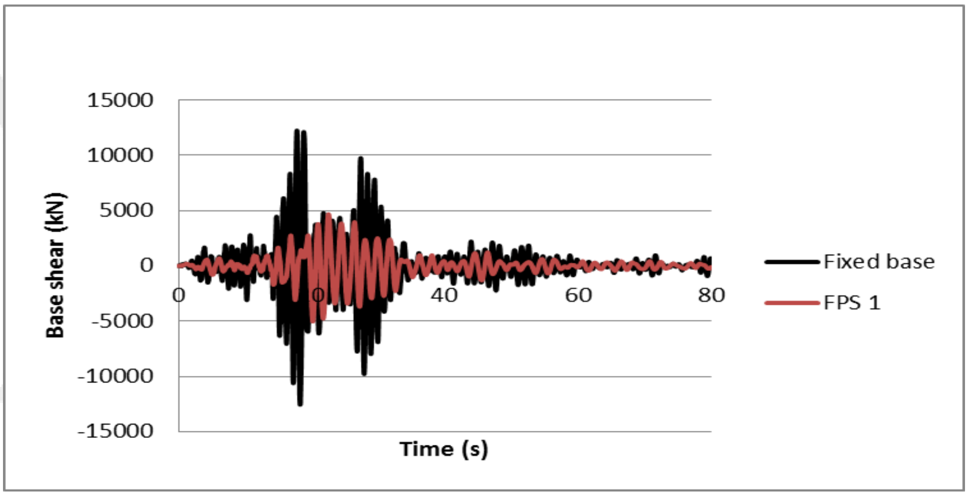


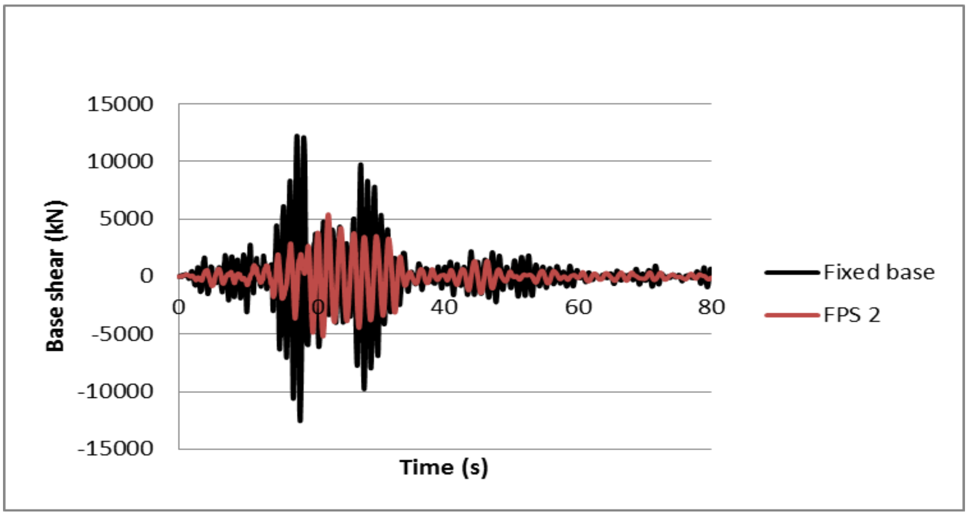
Figure 4.14 Variation inter-story drift ratio of fixed base system and FPS

4.2.4 Base shear time history

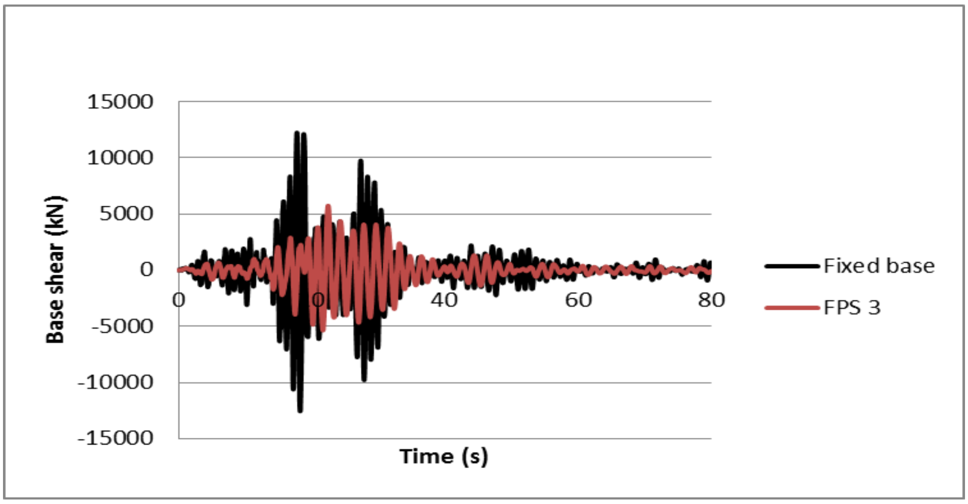
As shown in Figure 4.15, four different coefficients of friction (0.06, 0.09, 0.111 and 0.18) have been carried out with a radius of concave of 2.133 m under Yermo earthquake. As a result of comparison between curves, it has been shown that the larger the friction coefficient the later the isolation mechanism is activated. In an extreme case the base shear force does not overcome the friction force. In such a case, an isolated system responds the same as a classical fixed-base system. As a result of analysis, it has been found that the friction pendulum shows significant improvement in dynamic response of structure by reducing the base shear. For example, as shown in Figure 4.15, for the five story building, under the Yermo earthquake, the maximum base shear of the fixed - base system was about 11700 kN while the maximum base shear of the friction pendulum isolation systems considering different friction coefficients (0.06, 0.09, 0.111, and 0.18) was achieved as approximately 4900 kN, 5358 kN, 5740 kN and 6705 kN, respectively. As seen the figures, the results showed that the use of friction pendulum isolation system was better than of a fixed - base system, the maximum base shear demands were significantly smaller.



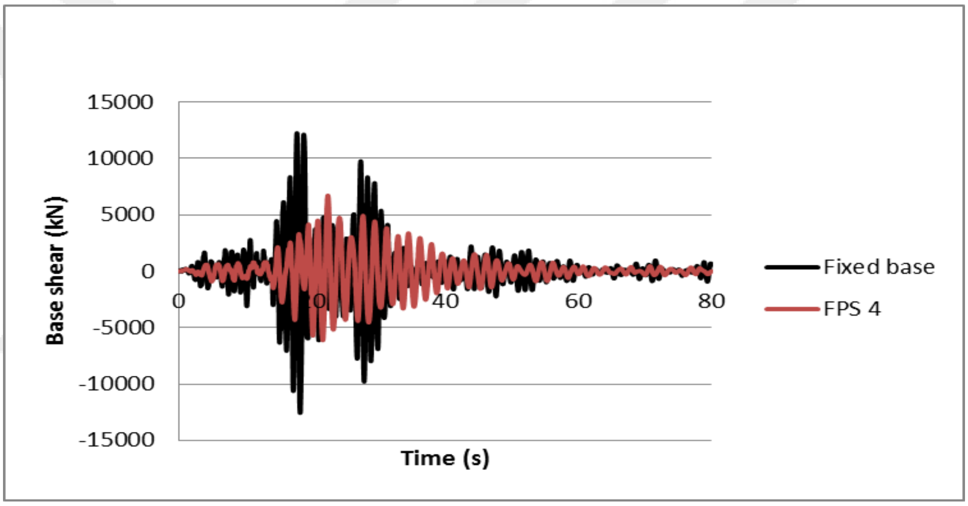
a)



b)



c)



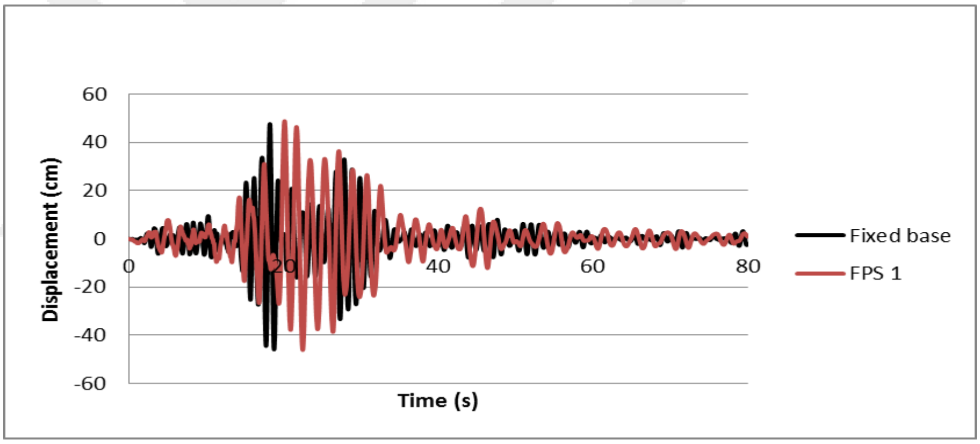
d)

Figure 4.15 Base shear time history of fixed base system and FPS with coefficient of friction of a) 0.06, b) 0.09, c) 0.111, and d) 0.18

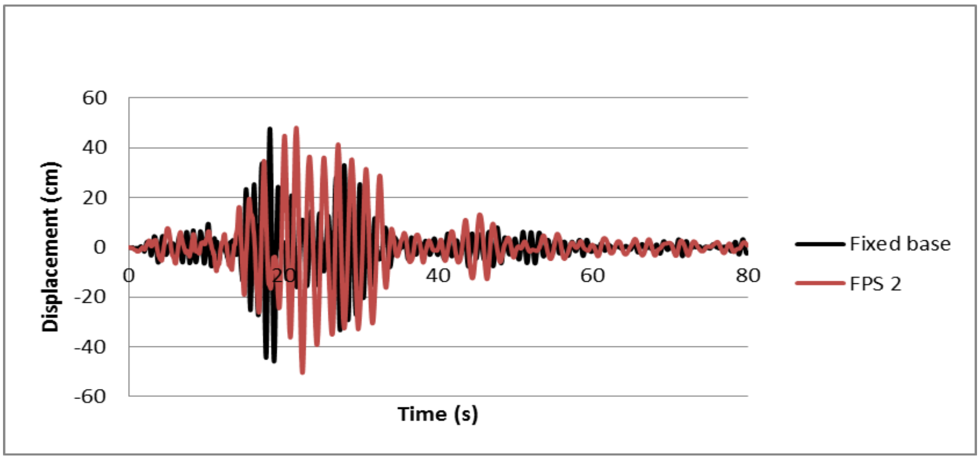
4.2.5 Roof displacement time history

Figure 4.16 shows the time history of the roof displacement of the fixed-base building and friction pendulum isolated building under Yermo earthquake for the 5 story structure. The used of the friction pendulum isolation system in the building remarkably decreased the value of roof displacement compared to the fixed-base system, especially in the case of structure with a friction pendulum isolation system with the lowest friction coefficient of 0.06 and then 0.09, 0.111 and 0.18, respectively.

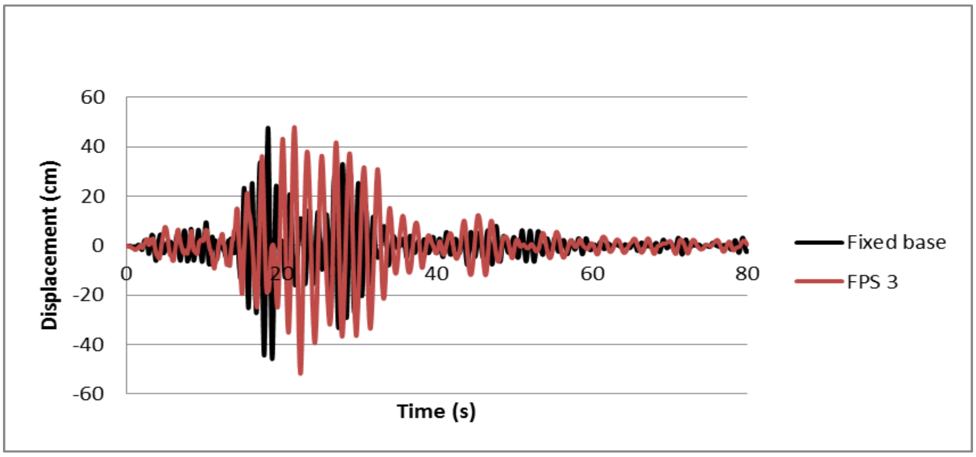
According to the results obtained from the nonlinear time history analysis, the friction pendulum isolation systems decreased significantly roof displacement of the existing building under Yermo earthquake. For example, as shown in Figure 4.16, for the five story building, under the Yermo earthquake, the maximum roof displacement of the fixed base system was about 47.9 cm while the maximum roof displacement of the friction pendulum isolation systems considering the various friction coefficients (0.06, 0.09, 0.111, and 0.18) was achieved as approximately 42.33 cm, 43.9 cm, 45.7 cm and 47.7 cm, respectively. Therefore, it could be observed generally that the addition of friction pendulum isolation system reduced significantly the drifts in the building. As seen the figures, the results showed that the use of friction pendulum isolation system was better than that of the fixed - base system and in the case of frames with friction pendulum isolated systems, the maximum roof drift demands were significantly smaller.



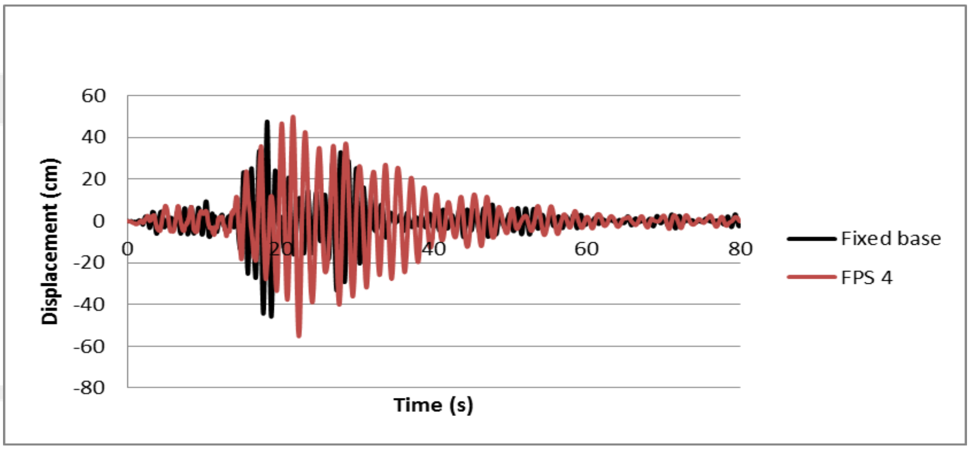
a)



b)



c)

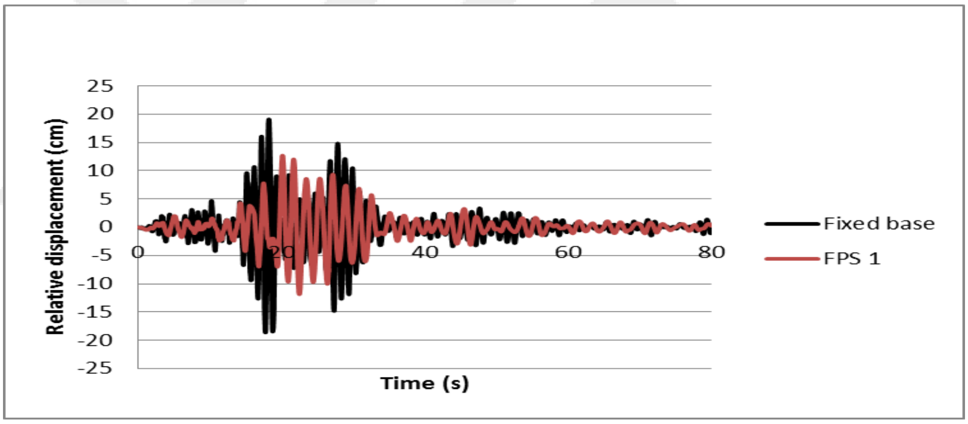


d)

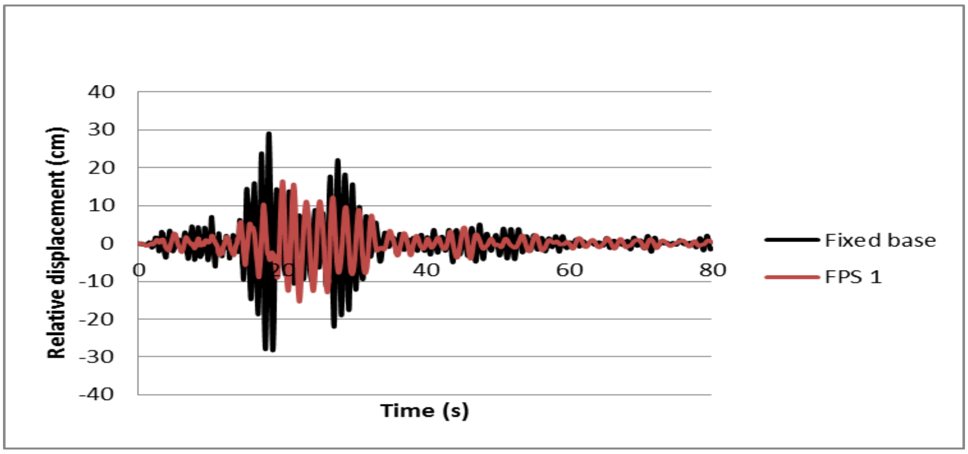
Figure 4.16 Displacement time history of fixed base system and FPS with coefficient of friction of a) 0.06, b) 0.09, c) 0.111, and d) 0.18

4.2.6 Relative displacement time history

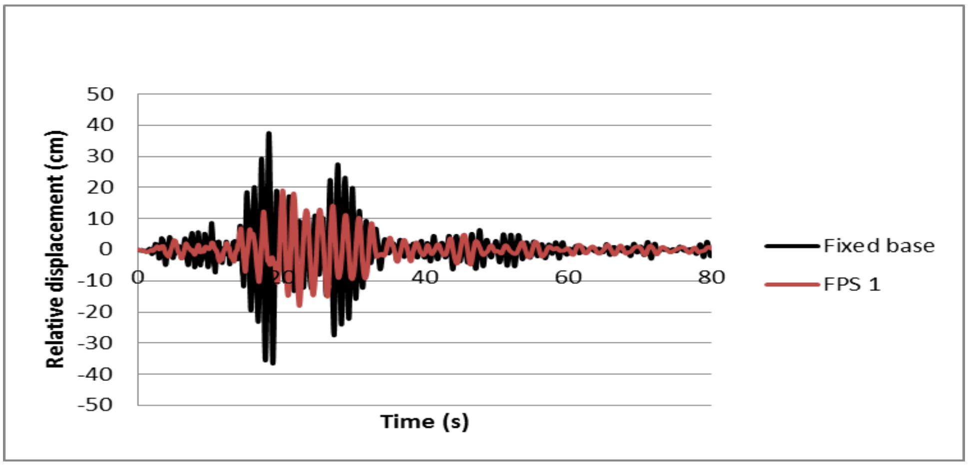
Figures 4.17 and 4.18 show the time history of the relative displacement for all floors of the 5 story building with the fixed-base system and friction pendulum isolation system under Yermo earthquake. The use of the friction pendulum isolation system in the building remarkably decreased the value of relative displacement compared to the fixed-base system, especially in the case of building with a friction pendulum isolation system with the lowest friction coefficient 0.06. According to the results obtained from the nonlinear time history analysis, the as shown in Figure 4.17, for the five story building, under the Yermo earthquake, the maximum relative displacement of the fixed base system was about 19.1 cm, 27.1 cm, 36.4 cm, 41.5 and 47 cm for each floor from 1 to 5, respectively, while the maximum relative displacement of the friction pendulum isolation systems considering friction coefficient of 0.06 was achieved as approximately 11.1 cm, 13.7 cm, 16 cm, 19 cm and 20.7 cm, respectively. When we used the 0.09 friction coefficient as in Figure 4.18, the relative displacement was as follows 12 cm, 15 cm, 19.2 cm, 20.9 cm and 21.4 cm for each floor from 1 to 5, respectively. As well as in Figures 4.19 and 4.20, the friction coefficients of 0.111 and 0.18, gave the relative displacement for the structure as follows (14.2 cm, 17.1 cm, 20.1 cm, 21.3 cm and 23.9 cm) and (16.7 cm, 19.3 cm, 24.2 cm, 26.5 cm and 28.6 cm) for each floor, respectively. Therefore, it could be observed generally that the addition of friction pendulum isolation systems reduced significantly the drifts in the building.



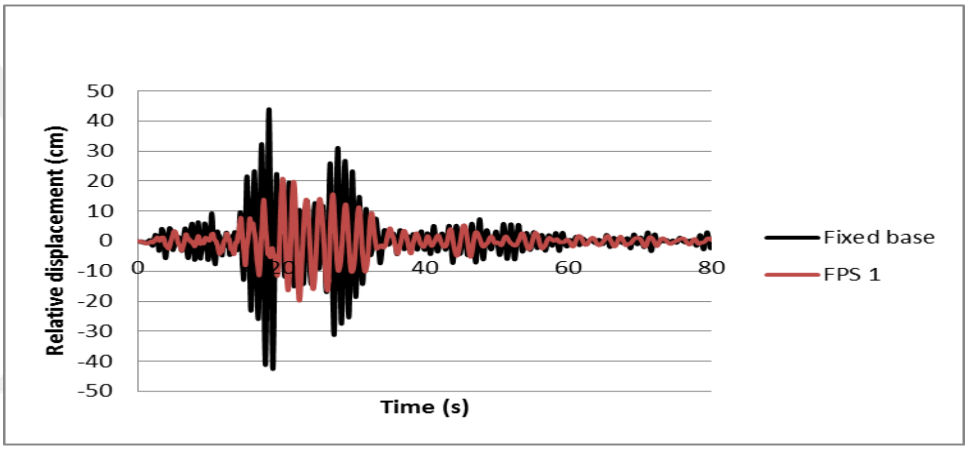
a)



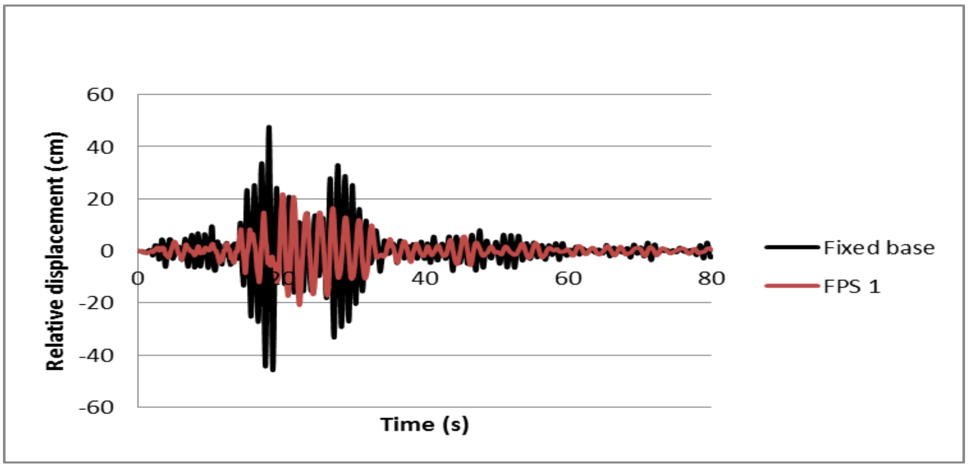
b)



c)

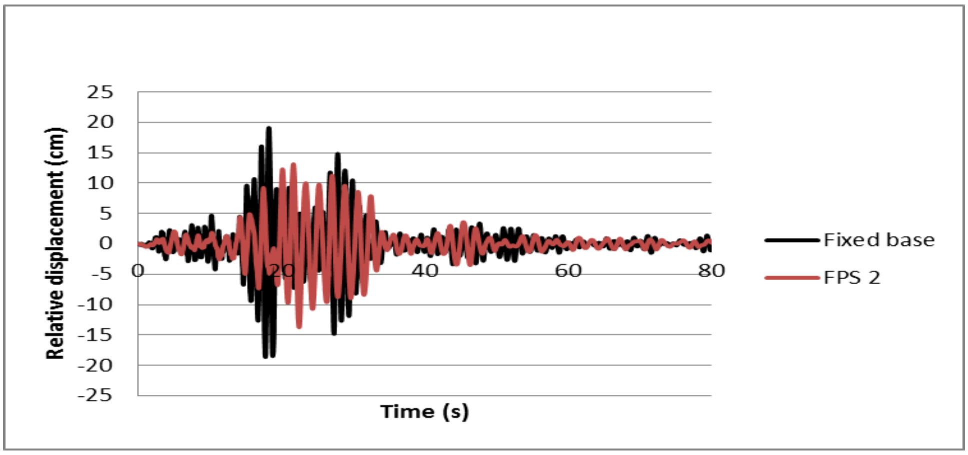


d)



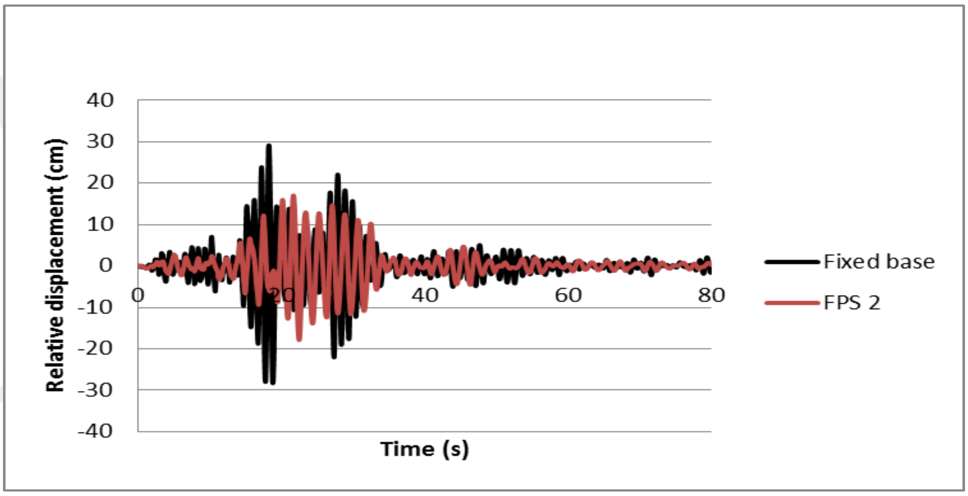
e)

Figure 4.17 Relative displacement vs. time for fixed base and FPS 1 cases at a) 1st, b) 2nd, c) 3rd, d) 4th, and e) 5th story levels



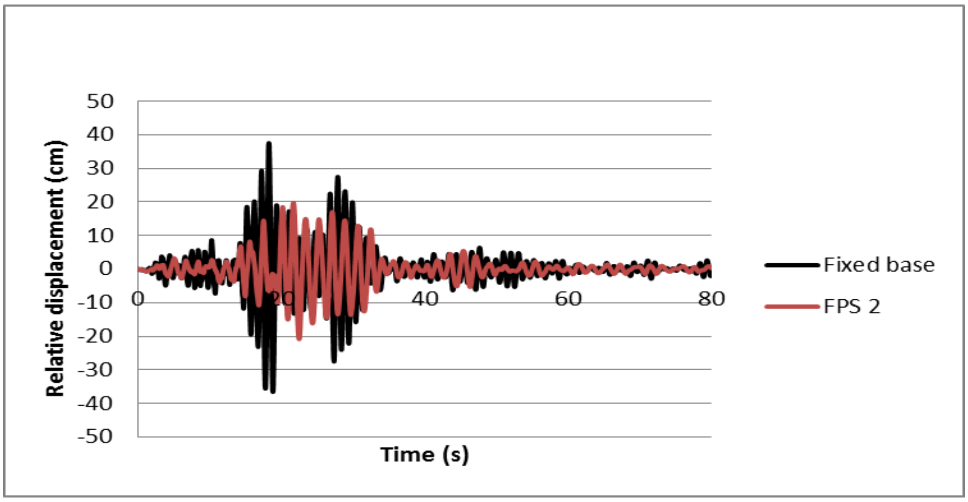
Relative displacement (cm)
Time (s)
Fixed base
FPS 2

a)



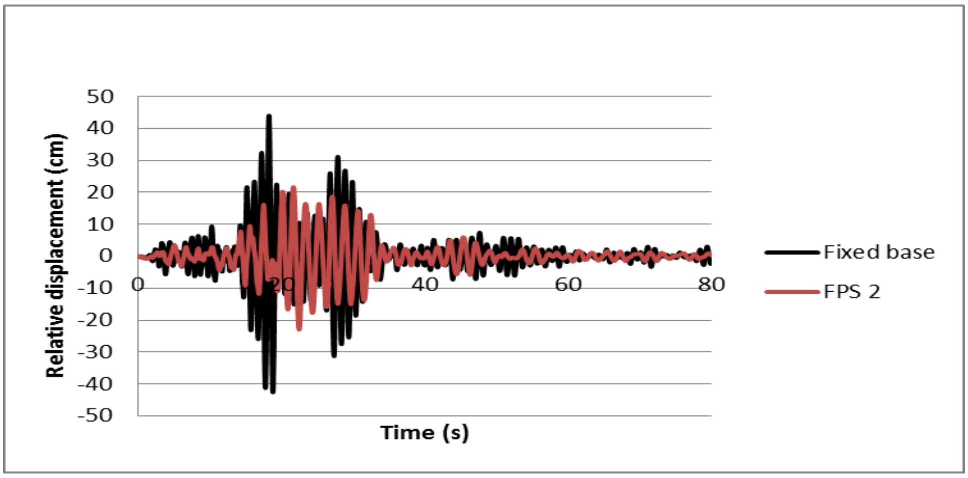
Relative displacement (cm)
Time (s)
Fixed base
FPS 2

b)

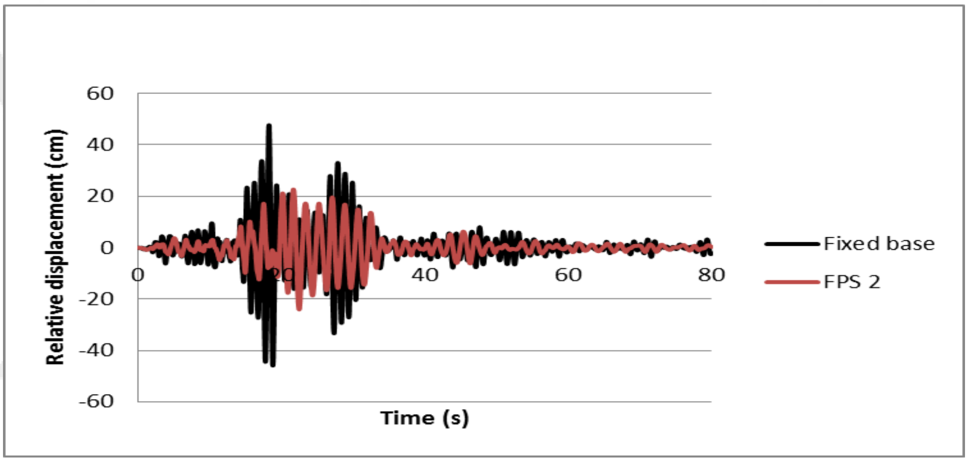


Relative displacement (cm)
Time (s)
Fixed base
FPS 2

c)

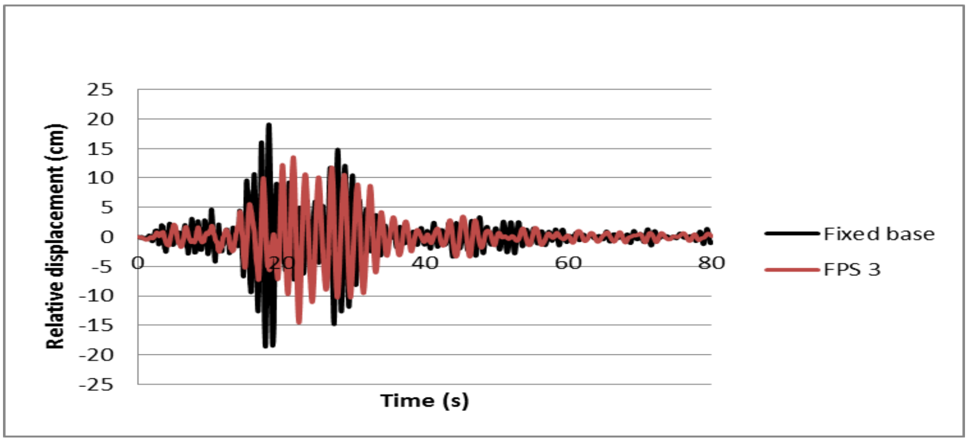


d)

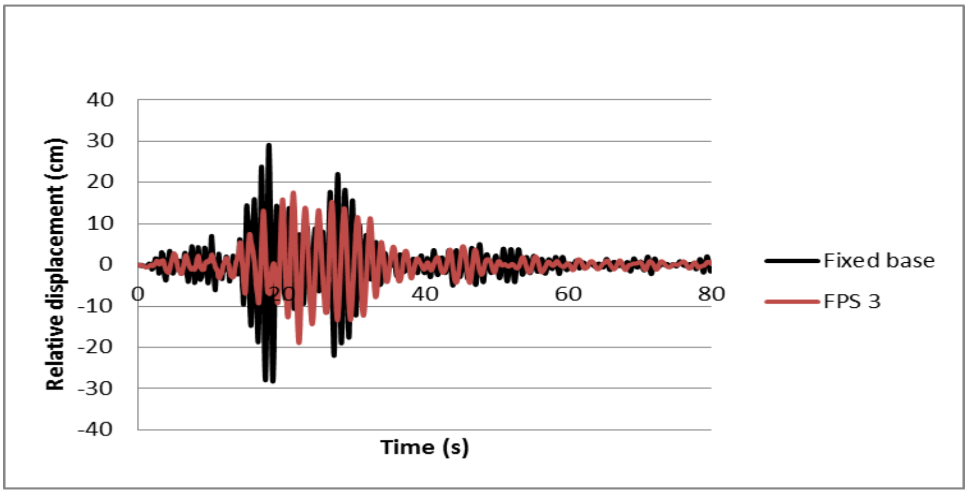


e)

Figure 4.18 Relative displacement vs. time for fixed base and FPS 2 cases at a) 1st, b) 2nd, c) 3rd, d) 4th, and e) 5th story levels

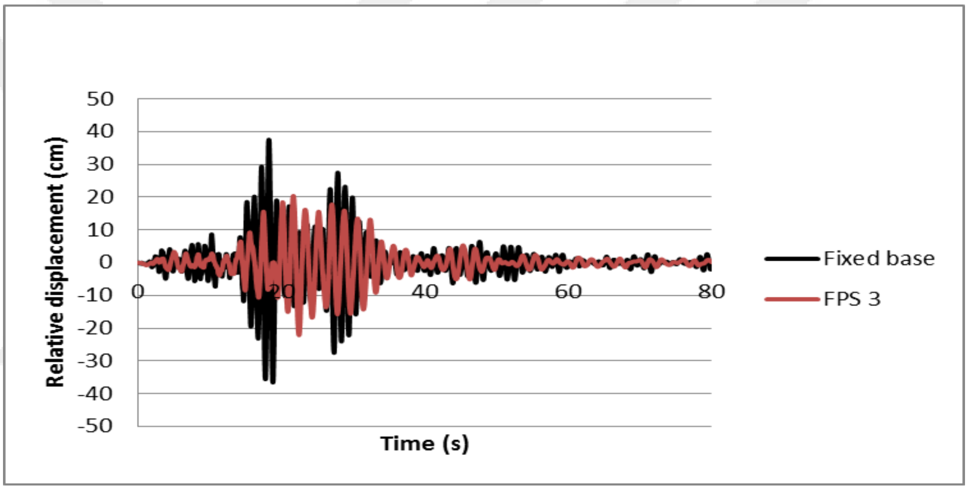


a)



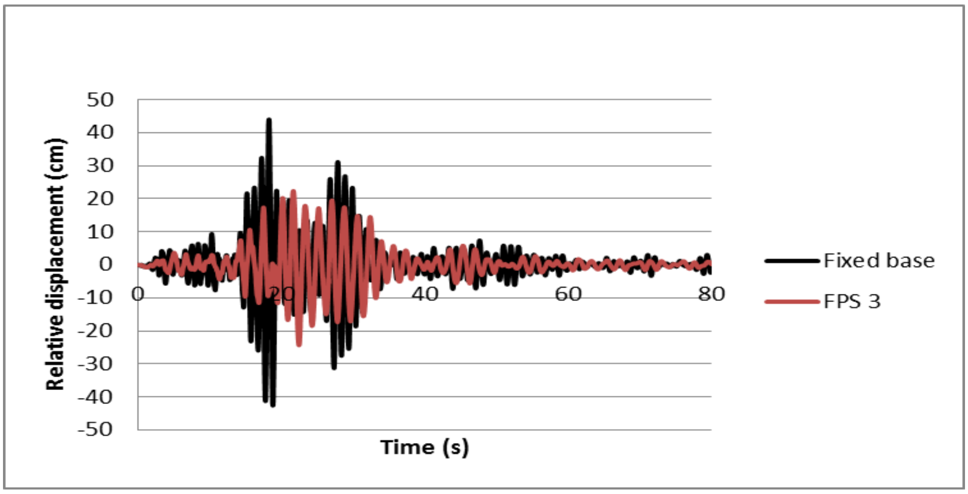
Relative displacement (cm)
40
30
20
10
0
-10
-20
-30
-40
0
20
40
60
80
Time (s)
Fixed base
FPS 3

b)



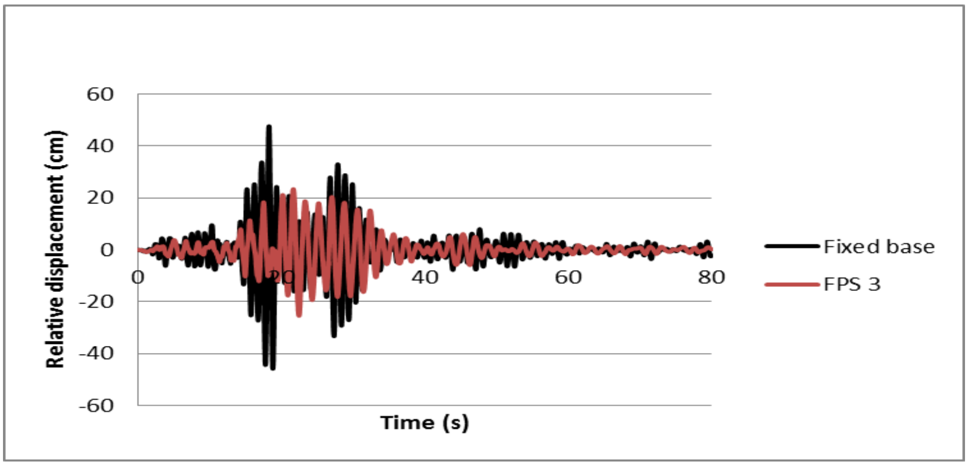
Relative displacement (cm)
50
40
30
20
10
0
-10
-20
-30
-40
-50
0
20
40
60
80
Time (s)
Fixed base
FPS 3

c)



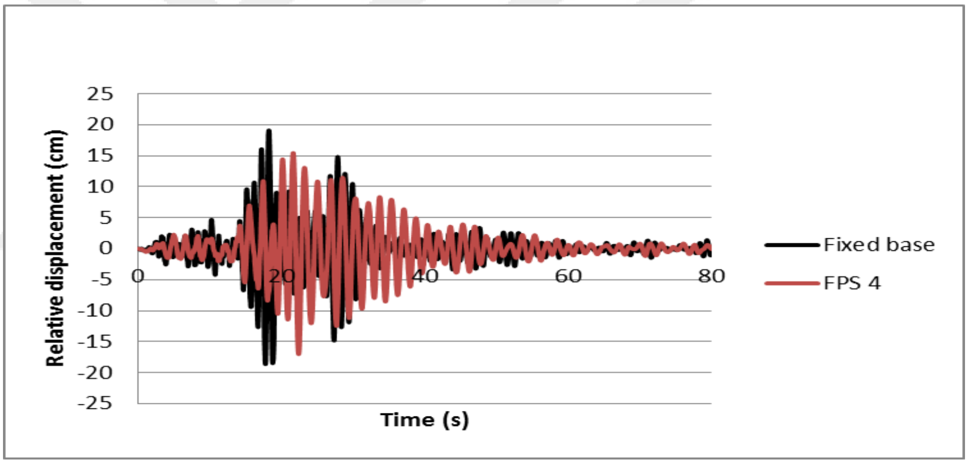
Relative displacement (cm)
50
40
30
20
10
0
-10
-20
-30
-40
-50
0
20
40
60
80
Time (s)
Fixed base
FPS 3

d)

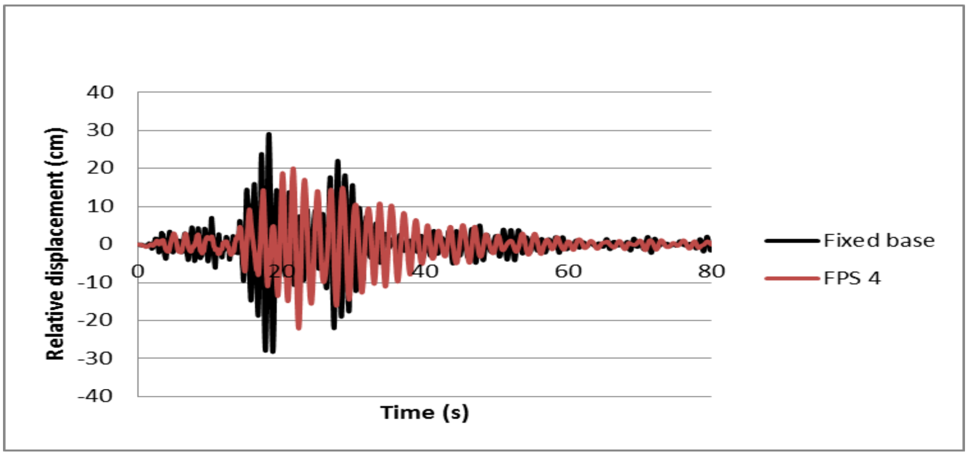


e)

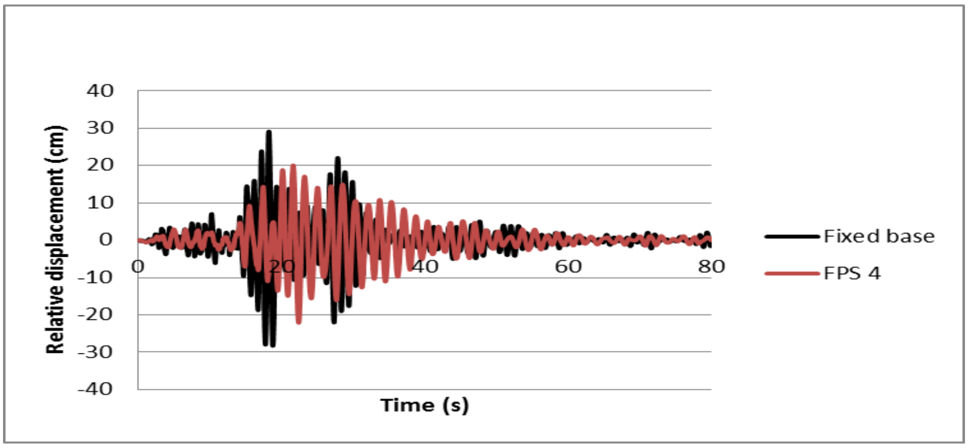
Figure 4.19 Relative displacement vs. time for fixed base and FPS 3 cases at a) 1st, b) 2nd, c) 3rd, d) 4th, and e) 5th story levels



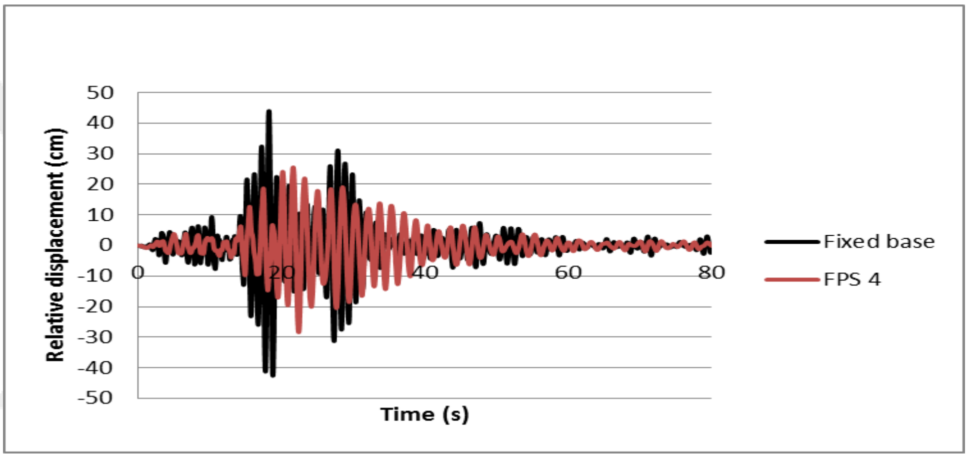
a)



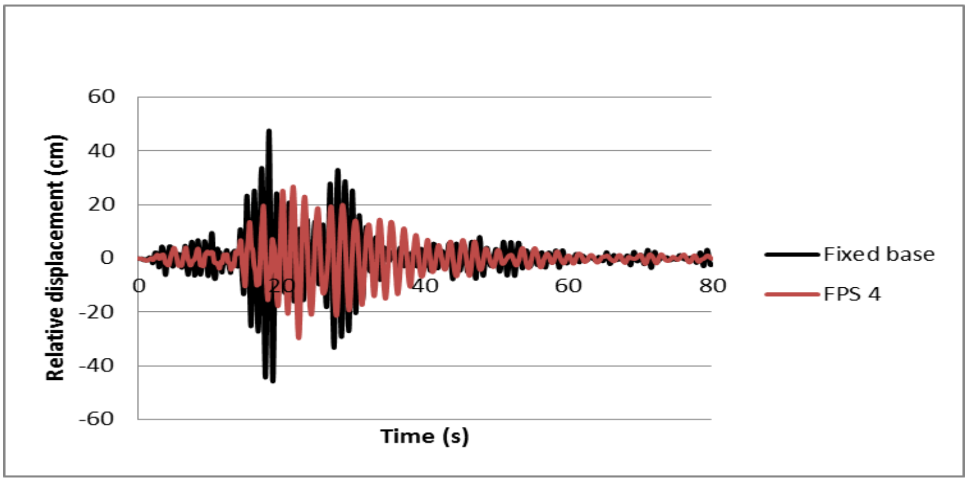
b)



c)



d)



e)

Figure 4.20 Relative displacement vs. time for fixed base and FPS 4 cases at a) 1st, b) 2nd, c) 3rd, d) 4th, and e) 5th story levels

4.2.7 Energy time history

The energy time history variation for the building with fixed base system and isolation system are given in Figure 4.21 and 4.22 respectively. The results of the analysis showed that the input energy under Yermo earthquake for the fixed base system was higher than that for the friction pendulum isolation system. It was found that decreasing the friction coefficient of FPS brought about marked increament in the energy dissipation capacity for the case study structure.

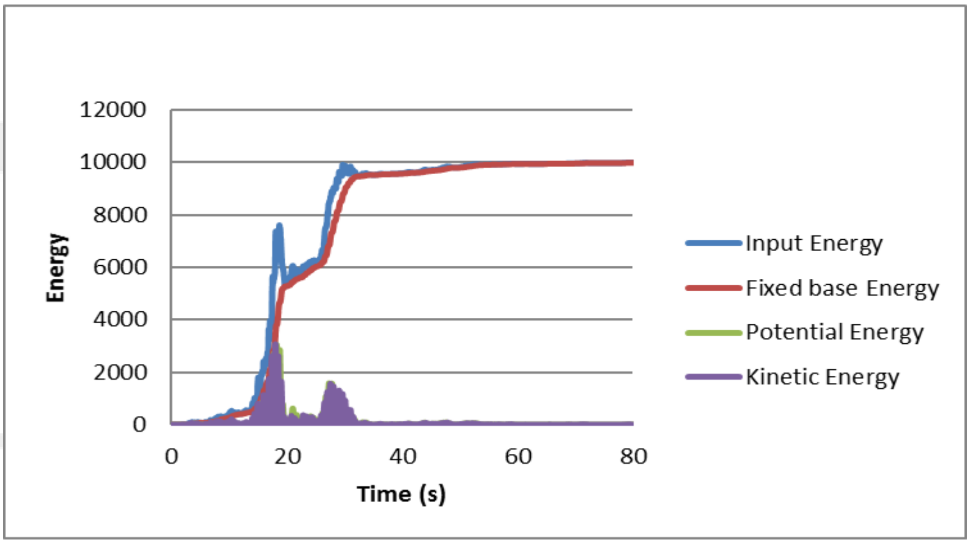
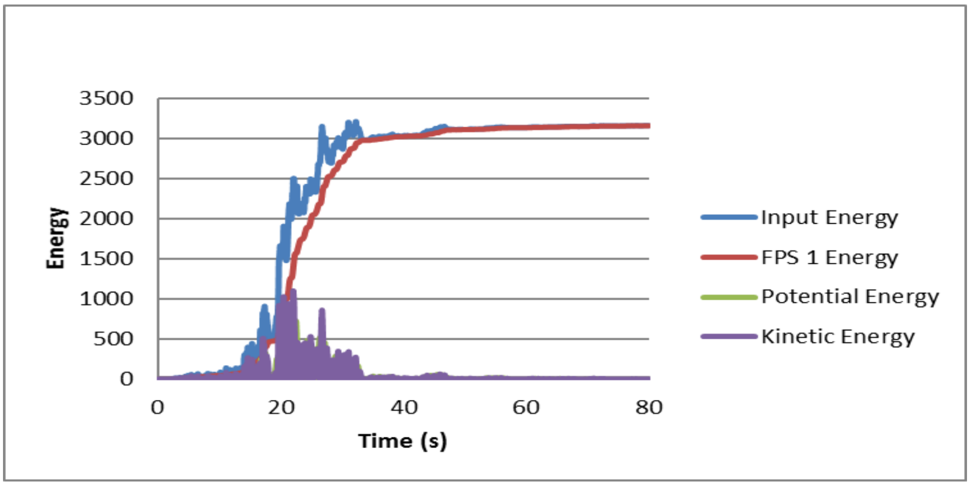
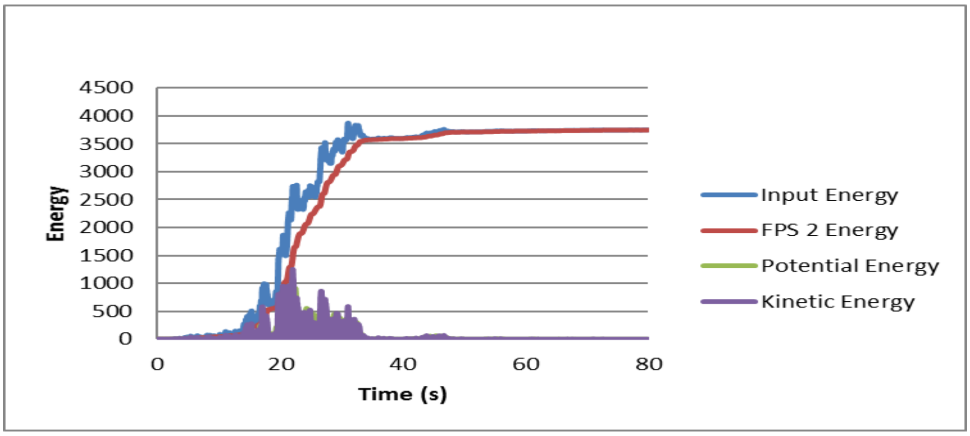


Figure 4.21 Energy within fixed base system under Yermo earthquake



a)



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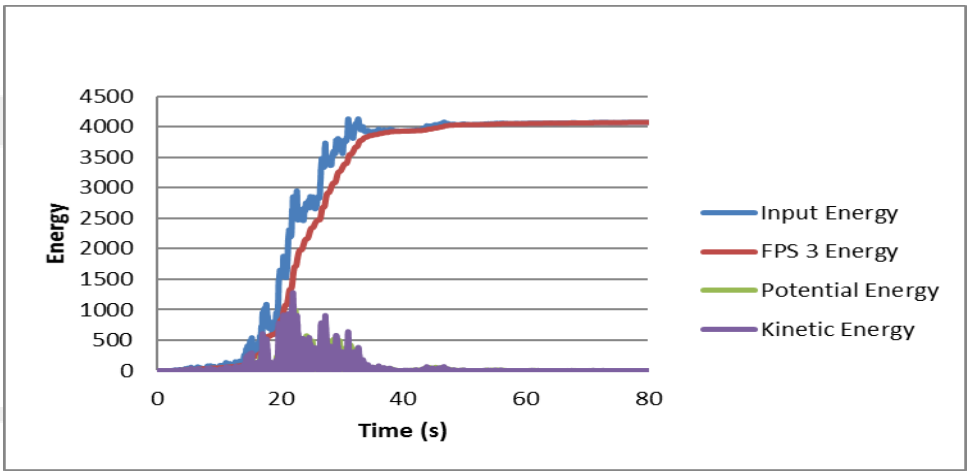
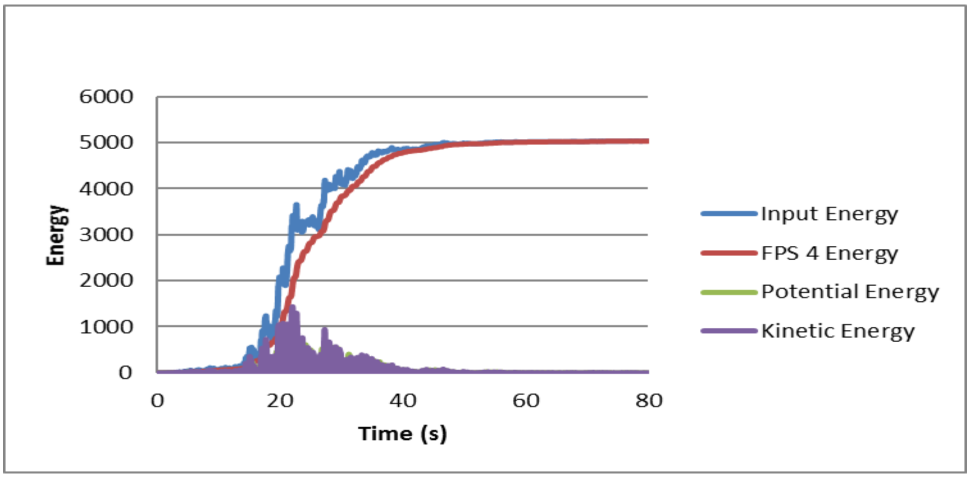


c)



d)

Figure 4.22 Energy within an isolated system under Yermo earthquake a) FPS 1, b) FPS 2, c) FPS 3, d) FPS 4

4.3 Analysis of results under Corralitos earthquake

4.3.1 Variation of story relative displacement

Figure 4.23 shows the variation of story relative displacements of the 5 story fixed-base building and upgraded by friction pendulum isolation. It was observed that all structures under investigation were considerably affected by the given earthquake. Moreover, the use of friction pendulum isolation for the purpose of enhancement decreased considerably the value of the maximum story relative displacements as compared to fixed-base case. For example, as seen in Figure 4.23, the five story building with fixed base under Corralitos earthquake, the maximum relative displacement was obtained as 67.48 cm while the maximum relative displacement in the case of the building with friction pendulum isolation systems with the friction coefficient of 0.06, 0.09, 0.111 and 0.18, obtained as 19.1, 22.53, 24.72 and 28.69 cm, respectively. As a result, it was appeared that the use of friction pendulum isolation systems with the lowest friction coefficient frames was better where decreased significantly the maximum displacement compare of the original frames with fixed base.

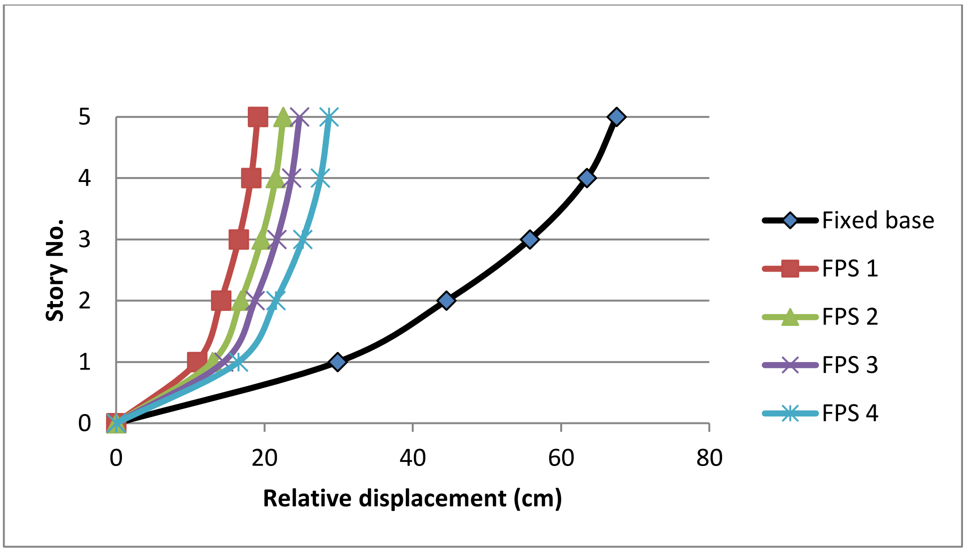


Figure 4.23 Relative displacement variation between fixed base system and FPS having different coefficients of friction

4.3.2 Variation of story relative drift

The plots for the relative drift of the structure with the fixed-base and friction pendulum isolation are given in Figure 4.24. According to the analysis of the results, the application of the friction pendulum isolation systems reduced significantly relative drift of the building under Corralitos earthquake as compared to the fixed base case. For example, as seen in Figure 4.24, for the five story building, under Corralitos earthquake, the maximum relative drift of the fixed-base system was achieved as 29.8 cm while the maximum relative drift of friction pendulum isolation system with coefficients of friction 0.06, 0.09, 0.111 and 0.18 was obtained as 10.9 cm, 12.9 cm, 14.4 cm and 16.46 cm, respectively.

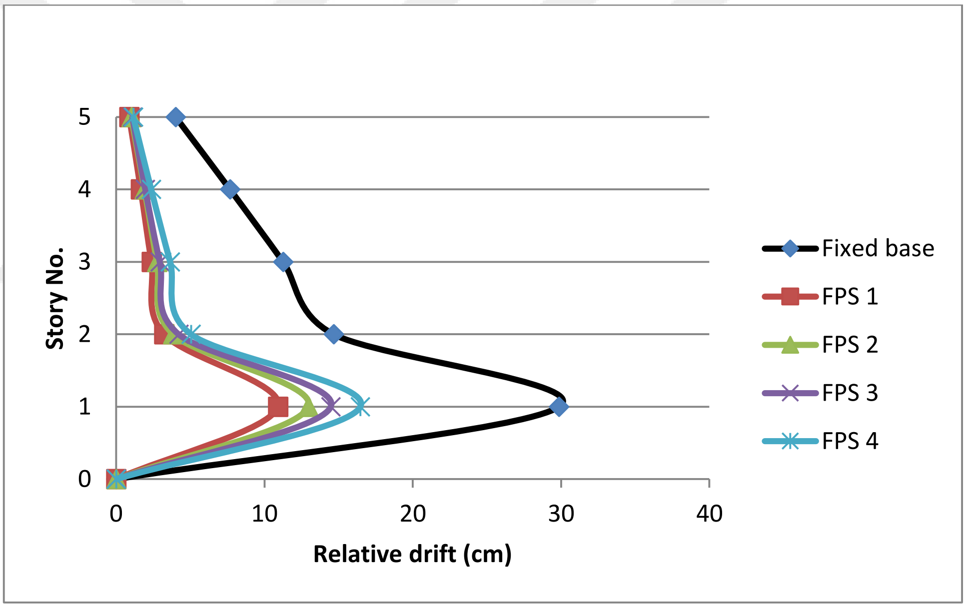


Figure 4.24 Relative drift variation between fixed base system and FPS

4.3.3 Inter-story drift ratio

The variation of the inter-story drift ratio of the fixed-base and isolated buildings are given in Figure 4.25. According to the analysis of the results, the friction pendulum isolation system led to the reduction in the inter-story drift ratio of the building in comparison to the fixed base case. For example, as seen in Figure 4.14, for the five story building, under Corralitos earthquake, the maximum inter-story drift ratio of the fixed-base system was obtained as 9.95%, while the maximum inter-story drift ratio of friction pendulum isolation systems with coefficients of friction 0.06, 0.09, 0.111 and 0.18 was recorded as 3.63%, 4.32%, 4,82% and 5.48%, respectively.

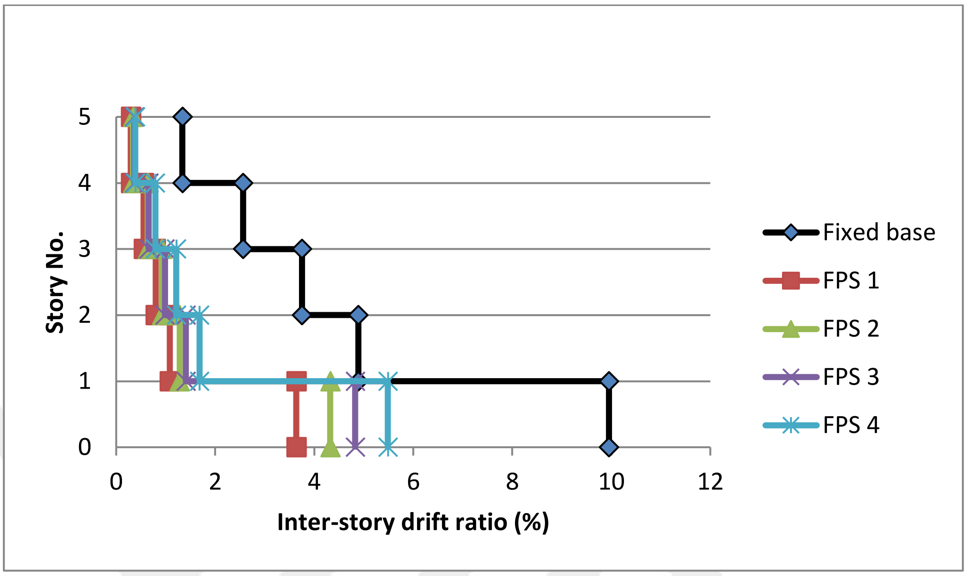
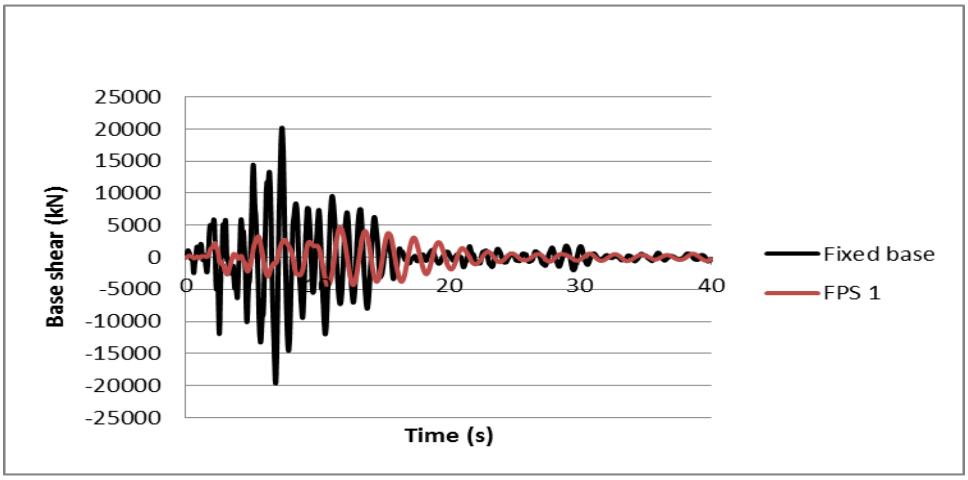


Figure 4.25 Variation inter-story drift ratio of fixed base system and FPS

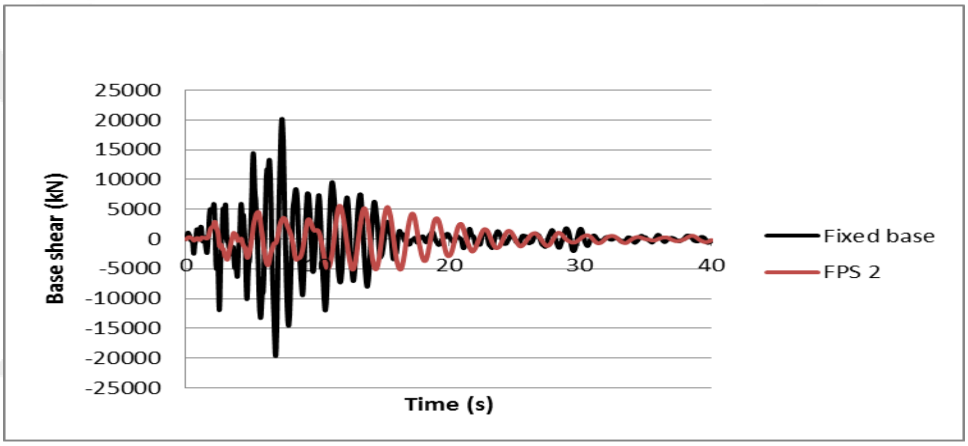
4.3.4 Base shear time history

Base shear vs. time variation is revealed in figure 4.26. As a result of comparison between curves, it has been shown that the larger the friction coefficient the lower the base shear for the case study building. Moreover, the highest base shear was observed in the building with fixed base while the lowest base shear was recorded in the building with FPS having 0,06 friction coefficient. From the Figure, for the five story building, under corralitos earthquake, the maximum base shear of the fixed -base system was about 20221 kN while the maximum base shear of the friction pendulum isolation systems considering the friction coefficient of 0.06, 0.09, 0.111, and 0.18 was achieved as approximately 4695 kN, 5620 kN, 6150 kN and 6544 kN, respectively. This clearly implied a reduction in the base shear value (from 3.1 to 4.3 times) due to the application of FPS to the building.



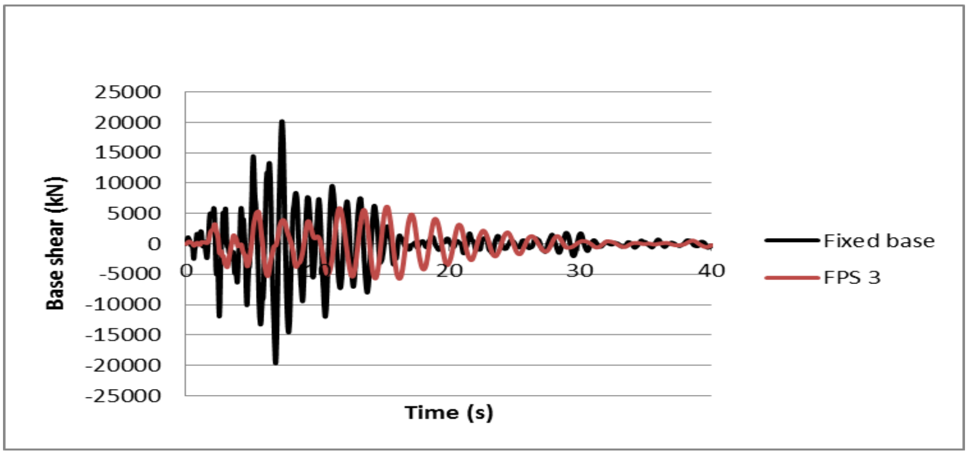
25000
20000
15000
10000
5000
0
-5000
-10000
-15000
-20000
-25000
0
20
30
40
Base shear (kN)
Time (s)
Fixed base
FPS 1

a)



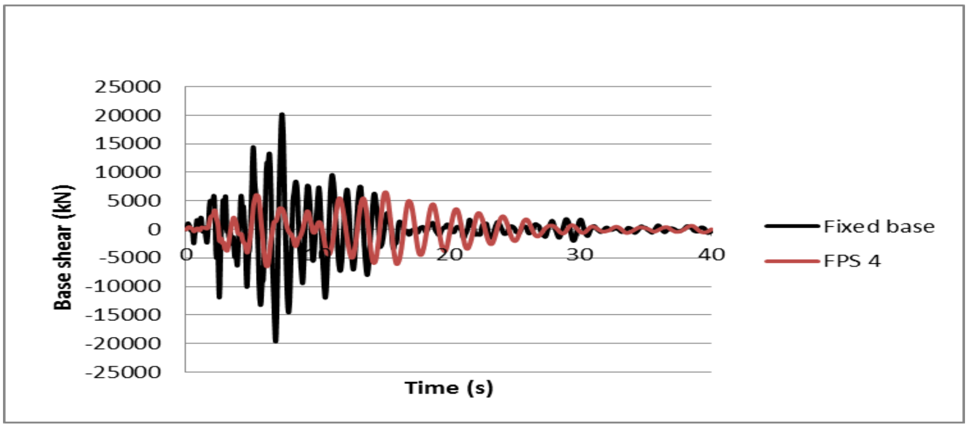
25000
20000
15000
10000
5000
0
-5000
-10000
-15000
-20000
-25000
0
20
30
40
Base shear (kN)
Time (s)
Fixed base
FPS 2

b)



25000
20000
15000
10000
5000
0
-5000
-10000
-15000
-20000
-25000
0
20
30
40
Base shear (kN)
Time (s)
Fixed base
FPS 3

c)

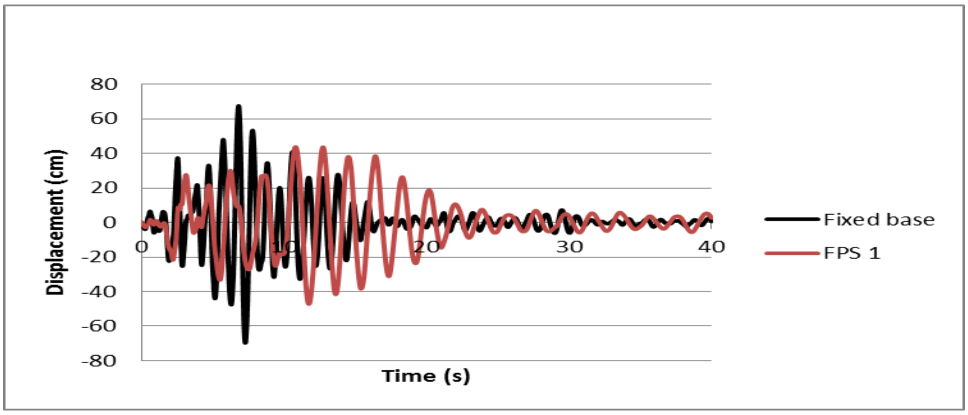


d)

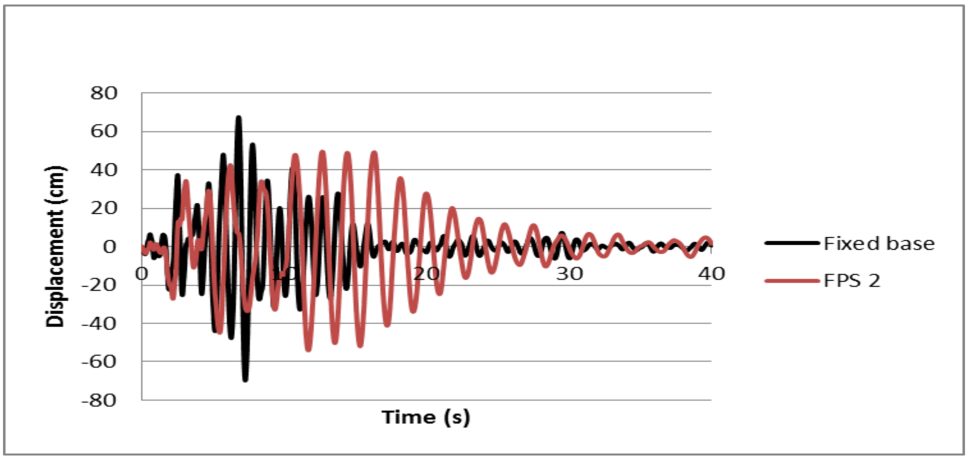
Figure 4.26 Base shear time history of fixed base system and FPS with coefficient of friction of a) 0.06, b) 0.09, c) 0.111, and d) 0.18

4.3.5 Roof displacement time history

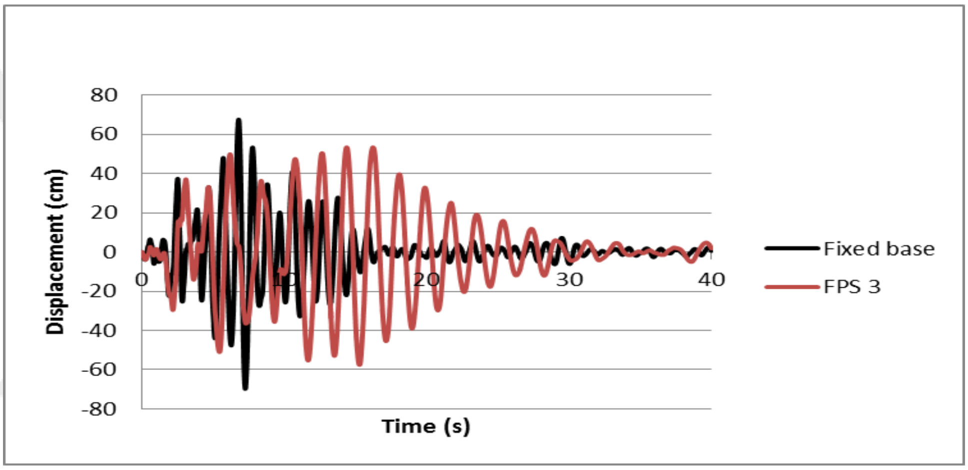
Figure 4.27 shows the time history of the roof displacement of the building with the fixed-base and base isolation. The use of the friction pendulum isolation system in the building remarkably decreased the value of roof displacement compared to the fixed-base system, For example, as shown in Figure 4.5, for the five story building, under Corralitos earthquake, the maximum roof displacement of the fixed base system was about 67.1 cm while the maximum roof displacement of the friction pendulum isolation systems considering different friction coefficients (0.06, 0.09, 0.111, and 0.18) was achieved as approximately 44.2 cm, 52.23 cm, 54.3 cm and 55.5 cm, respectively. Therefore, it could be observed generally that the addition of friction pendulum isolation systems reduced significantly the drifts in the building.



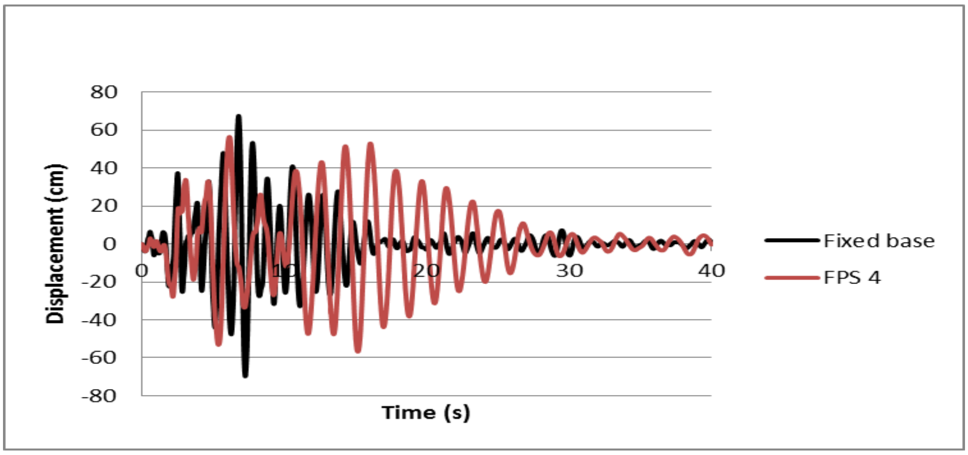
a)



b)



c)

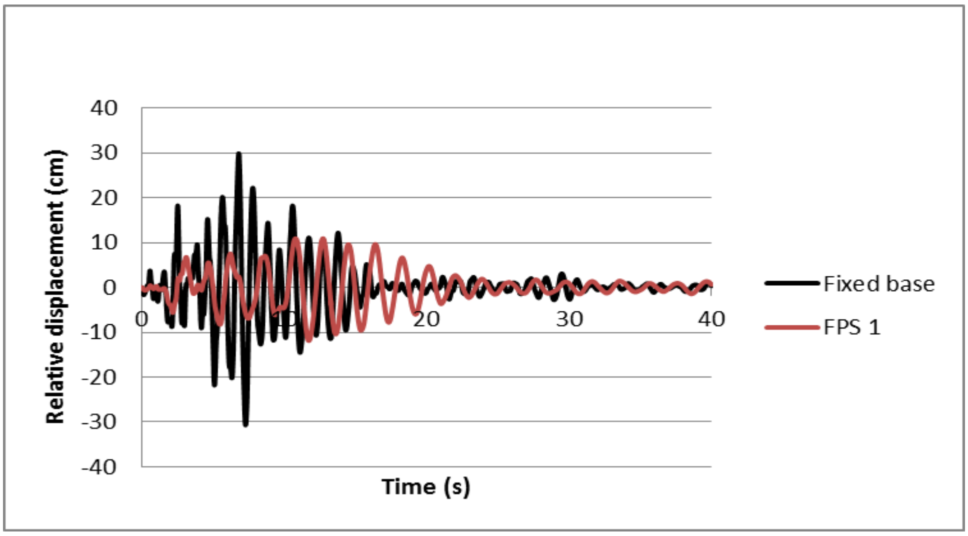


d)

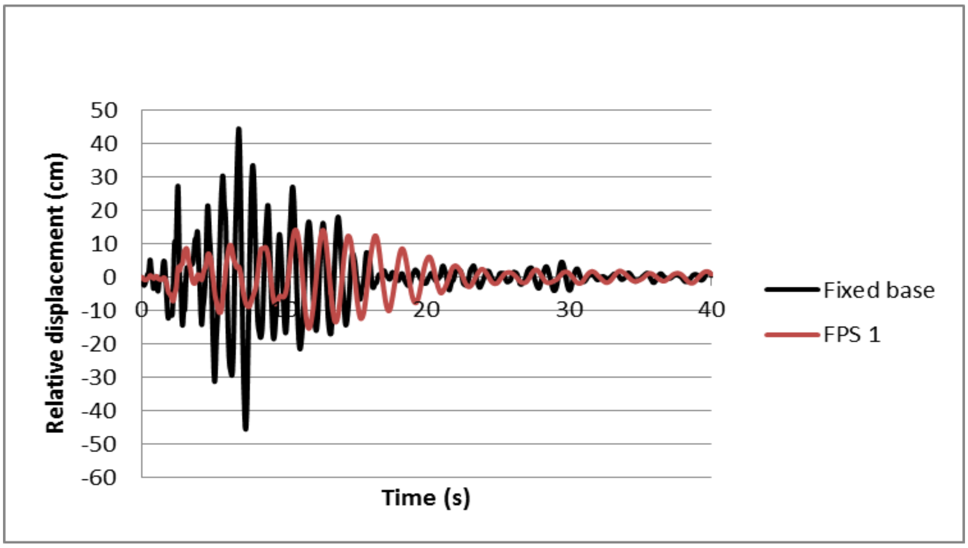
Figure 4.27 Displacement time history of fixed base system and FPS with coefficient of friction of a) 0.06, b) 0.09, c) 0.111, and d) 0.18

4.3.6 Relative displacement time history

Figures 4.28 and 4.29 show the time history of the relative displacement for all floors of the building for the fixed-base and base isolation case. According to the results obtained from the nonlinear time history analysis, as shown in the Figures, for the five story building under Corralitos earthquake, the maximum relative displacement of fixed base system was about 30.1 cm, 45.1 cm, 56.2 cm, 64.1 cm and 68.6 cm for each floor from 1 to 5, respectively, while the maximum relative displacement of the friction pendulum isolation systems considering a friction coefficient of 0.06 was achieved as approximately 10.4, 13.9, 15.1, 19.7 and 20.42 cm, respectively. When we used the 0.09 friction coefficient, the relative displacement was as 13.17, 17.1, 19.4, 22.7 and 24,45 cm for each floor from 1 to 5, respectively. In the case of the friction coefficient of 0.111 and 0.18 the relative displacement was found as (14.3 cm, 17.4 cm, 20.3 cm, 22.5 cm and 24.1 cm) and (15.1 cm, 20.1 cm, 22.6 cm, 25.2 cm and 26.9 cm) for each floor, respectively. Therefore, it could be observed generally that the addition of friction pendulum isolation systems reduced significantly the drifts in the building.

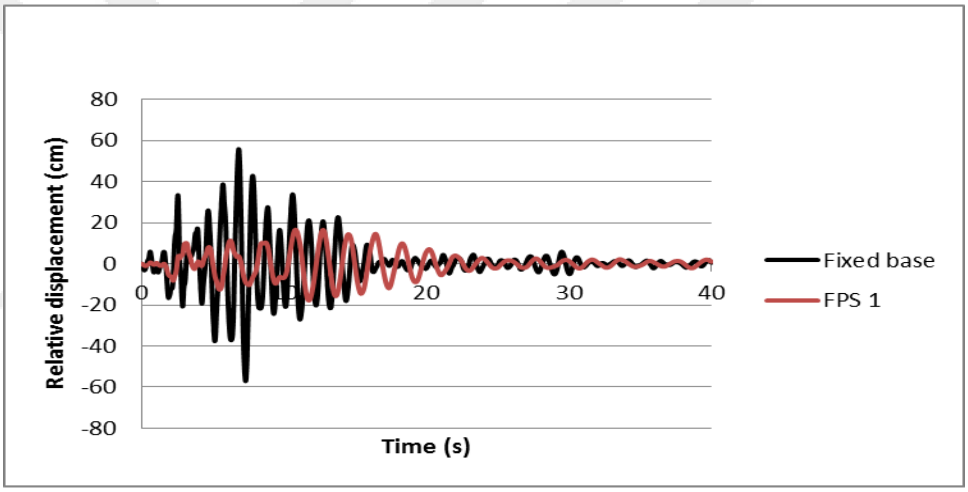


a)



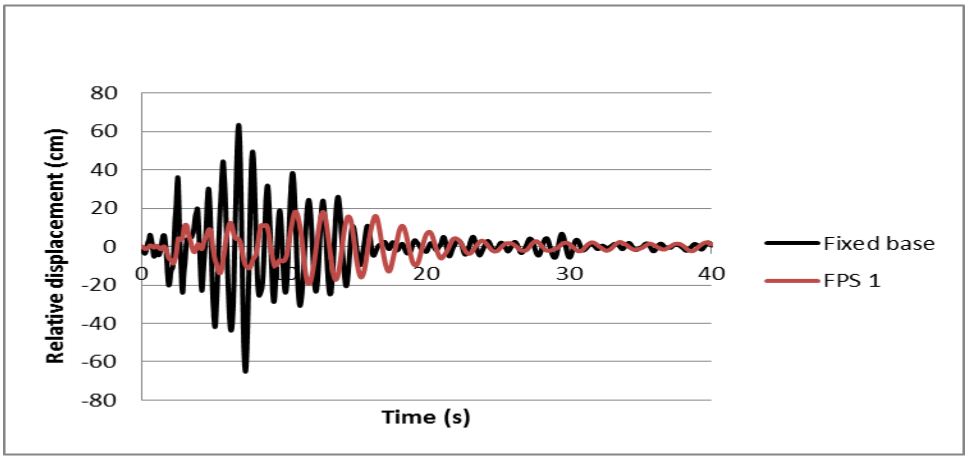
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
0
20
30
40
Relative displacement (cm)
Time (s)
Fixed base
FPS 1

b)



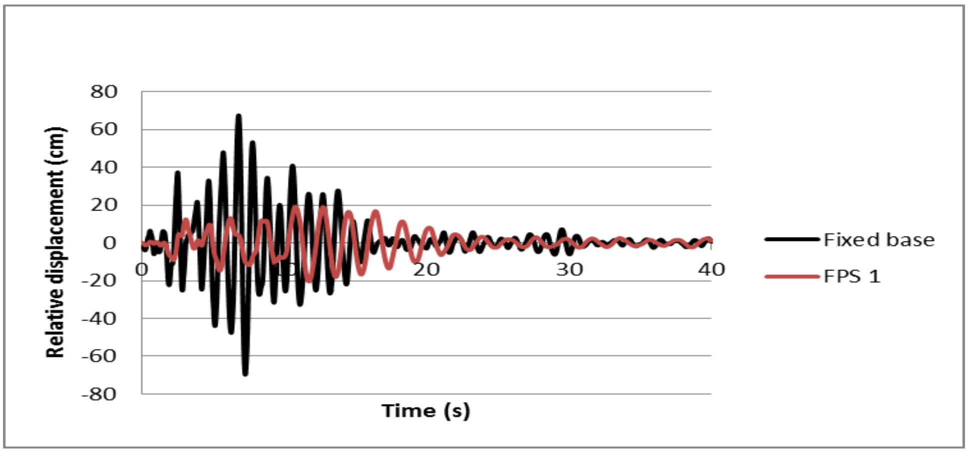
80
60
40
20
0
-20
-40
-60
-80
0
20
30
40
Relative displacement (cm)
Time (s)
Fixed base
FPS 1

c)



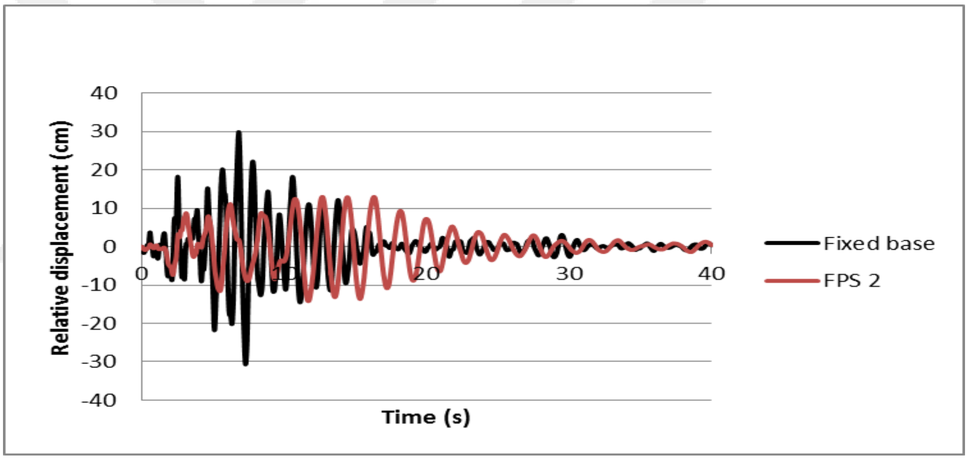
80
60
40
20
0
-20
-40
-60
-80
0
20
30
40
Relative displacement (cm)
Time (s)
Fixed base
FPS 1

d)

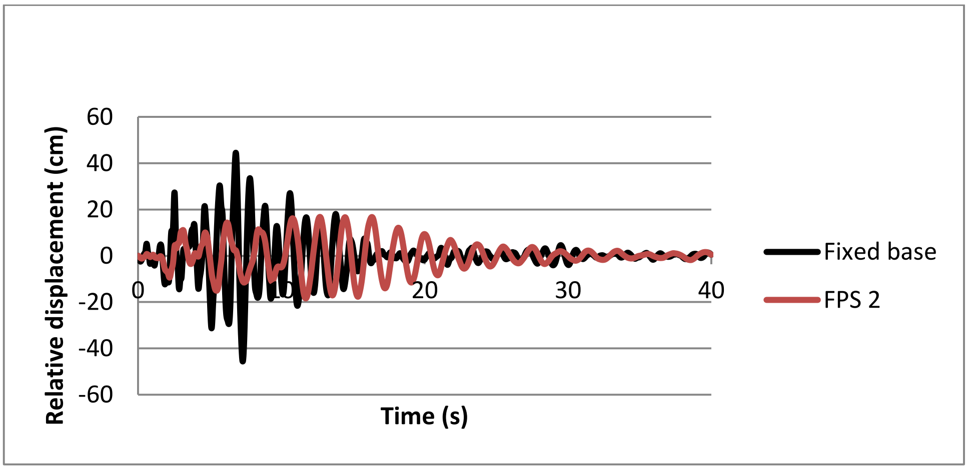


e)

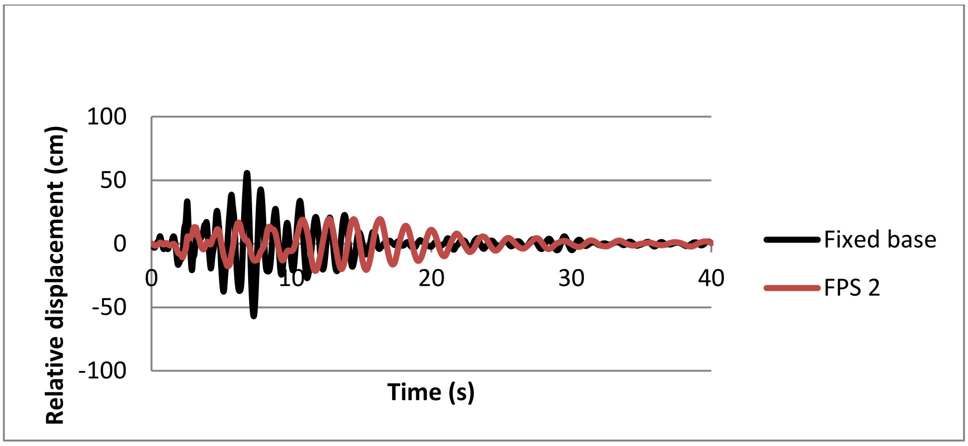
Figure 4.28 Relative displacement vs. time for fixed base and FPS 1 cases at a) 1st, b) 2nd, c) 3rd, d) 4th, and e) 5th story levels



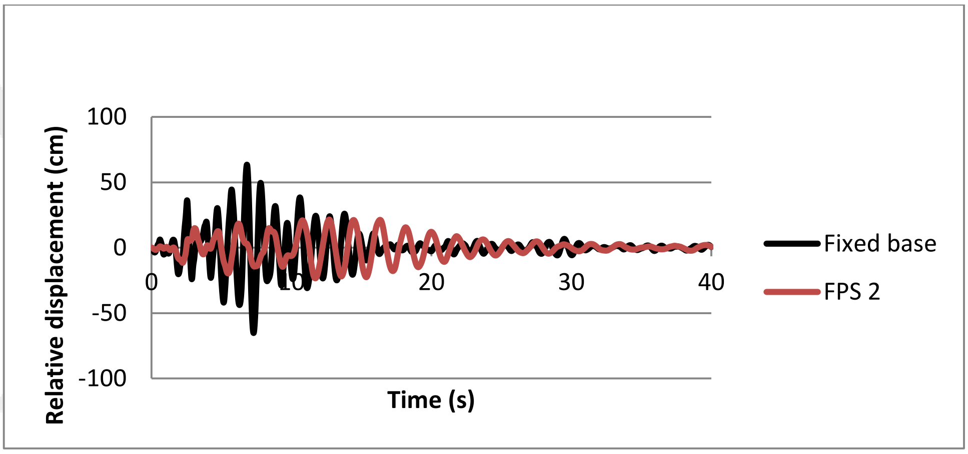
a)



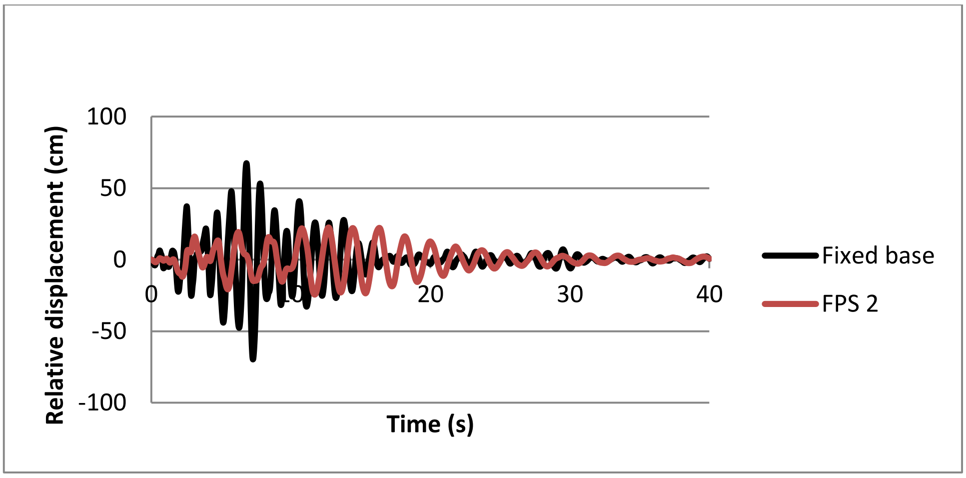
b)



c)

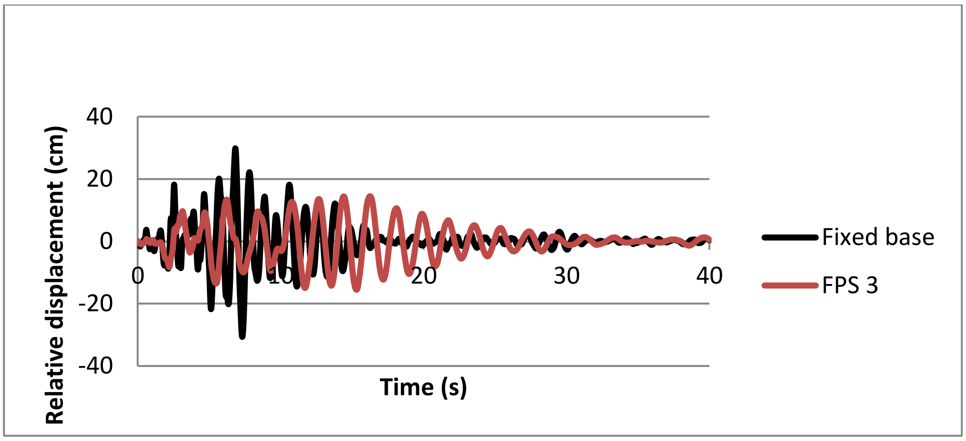


d)

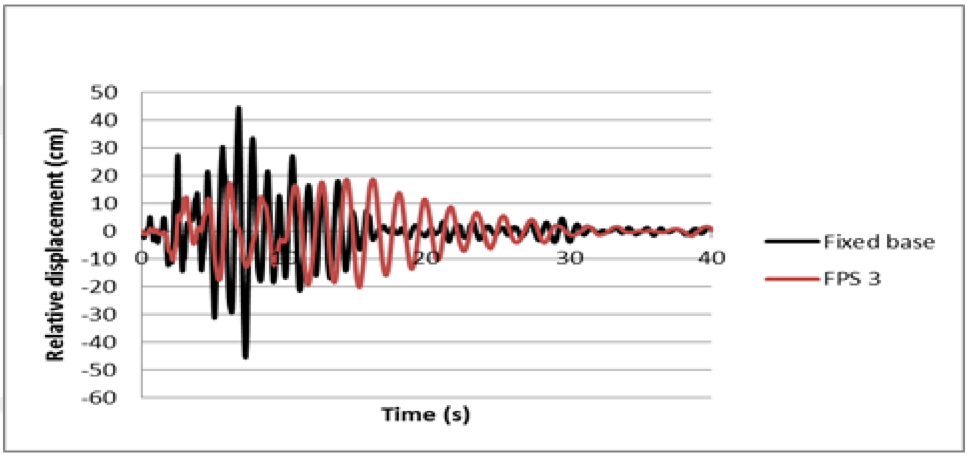


e)

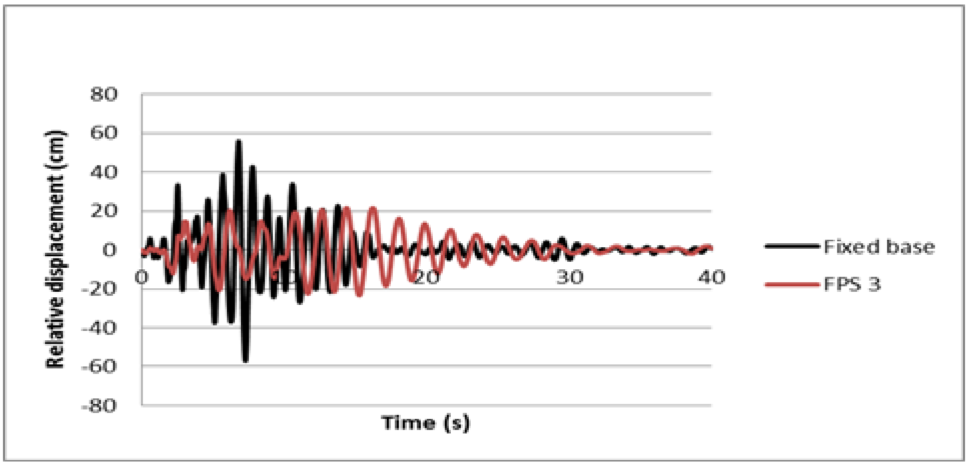
Figure 4.29 Relative displacement vs. time for fixed base and FPS 2 cases at a) 1st, b) 2nd, c) 3rd, d) 4th, and e) 5th story levels


Relative displacement (cm)
40
20
0
-20
-40
0
10
20
30
40
Time (s)
Fixed base
FPS 3

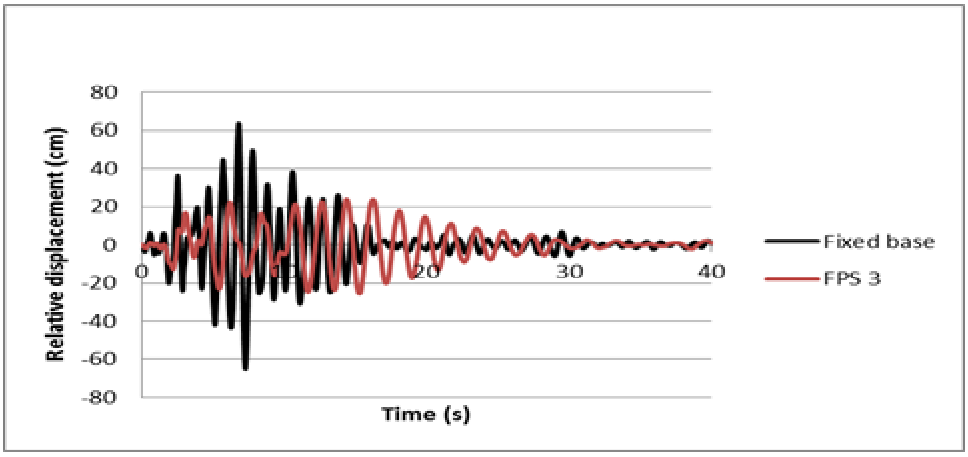
a)


Relative displacement (cm)
50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
0
20
30
40
Time (s)
Fixed base
FPS 3

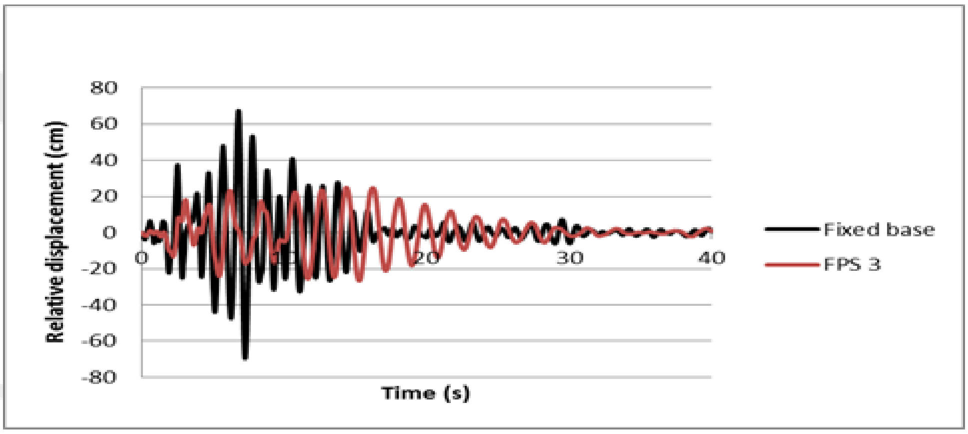
b)


Relative displacement (cm)
80
60
40
20
0
-20
-40
-60
-80
0
20
30
40
Time (s)
Fixed base
FPS 3

c)

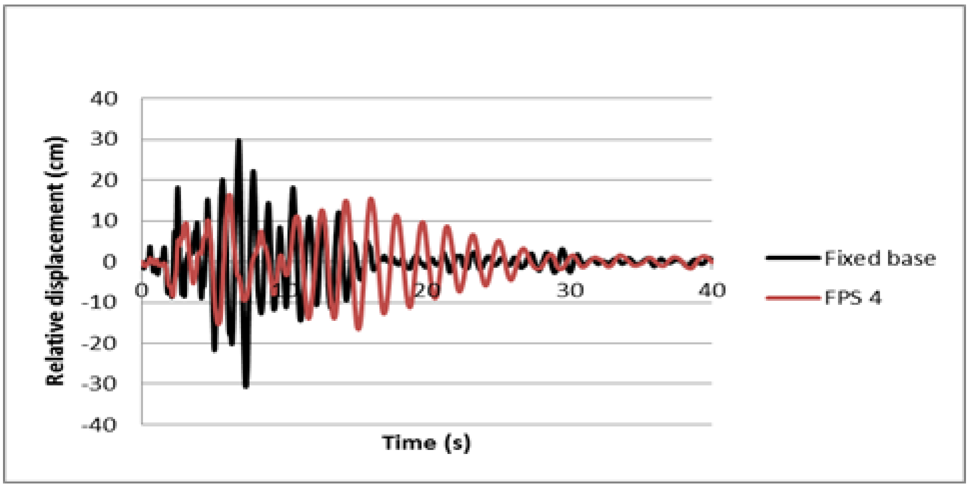


d)

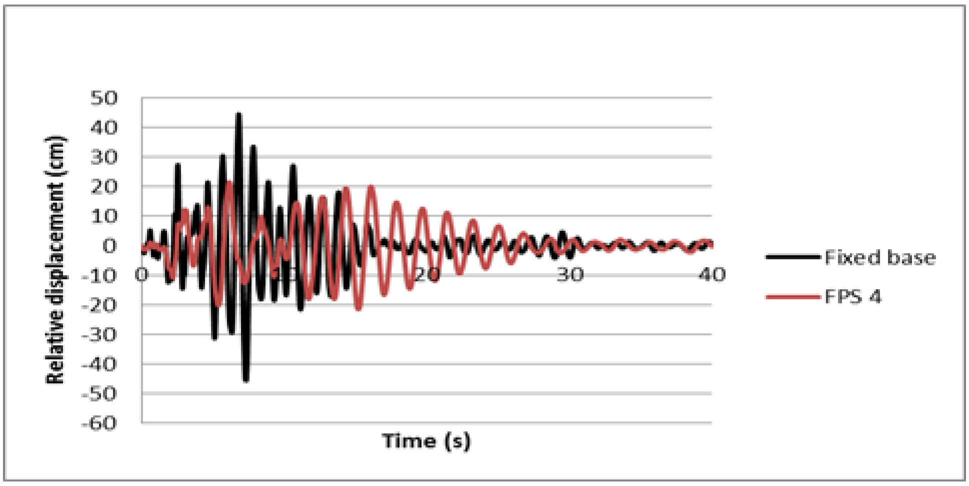


e)

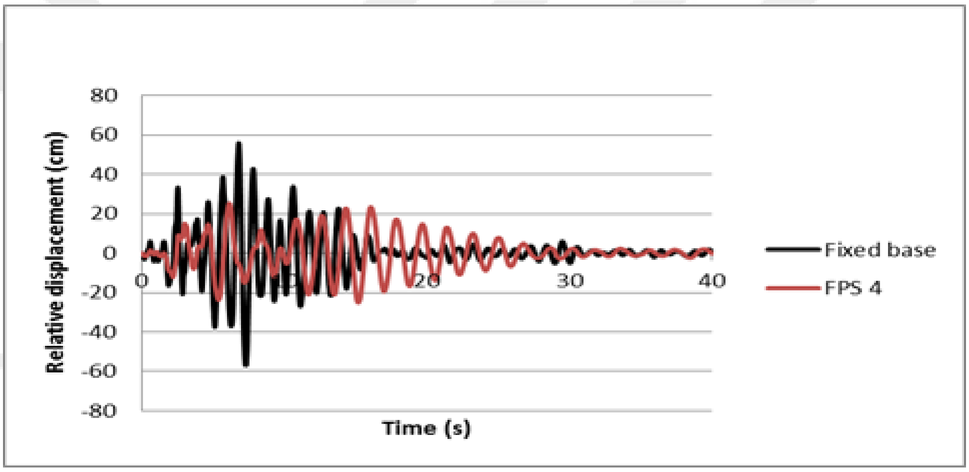
Figure 4.30 Relative displacement vs. time for fixed base and FPS 3 cases at a) 1st, b) 2nd, c) 3rd, d) 4th, and e) 5th story levels



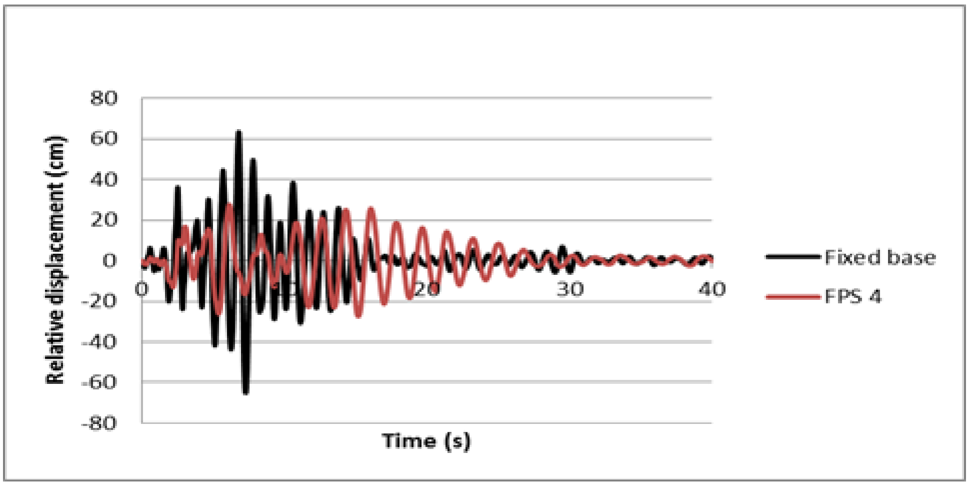
a)


50
40
30
20
10
0
-10
-20
-30
-40
-50
-60
0
30
40
Relative displacement (cm)
Time (s)
Fixed base
FPS 4

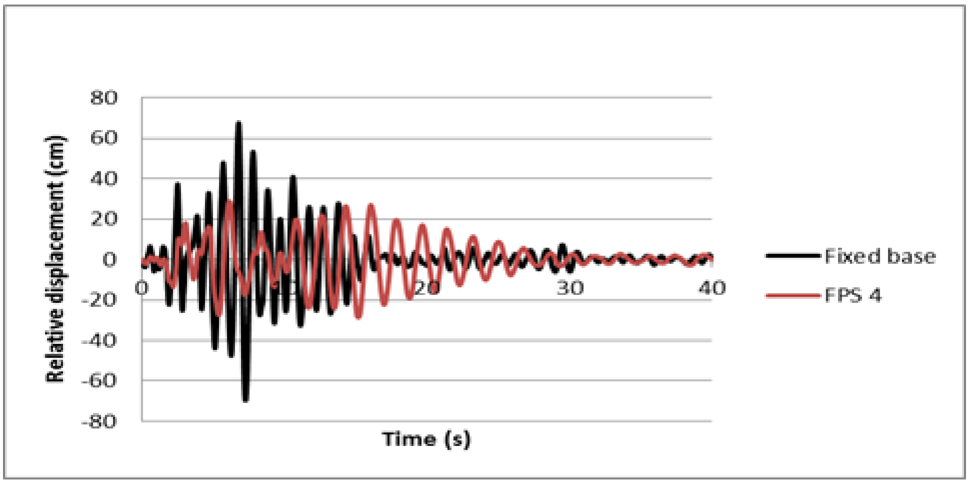
b)


80
60
40
20
0
-20
-40
-60
-80
0
30
40
Relative displacement (cm)
Time (s)
Fixed base
FPS 4

c)


80
60
40
20
0
-20
-40
-60
-80
0
30
40
Relative displacement (cm)
Time (s)
Fixed base
FPS 4

d)



e)

Figure 4.31 Relative displacement vs. time for fixed base and FPS 4 cases at a) 1st, b) 2nd, c) 3rd, d) 4th, and e) 5th story levels

4.3.7 Energy time history

The variation in the energy time history for the fixed base and base isolation cases Corralitos earthquake are given in Figures 4.32 and 4.33. Similar to the previous results obtained under Pomona and Yermo earthquake, the fixed base case resulted in higher energy values than the base isolated case. Moreover, among the base isolation cases, the FPS with lower friction coefficient yield higher energy values. The analysis of the results showed that the design of FPS for the building was very important to achieve more energy dissipation.

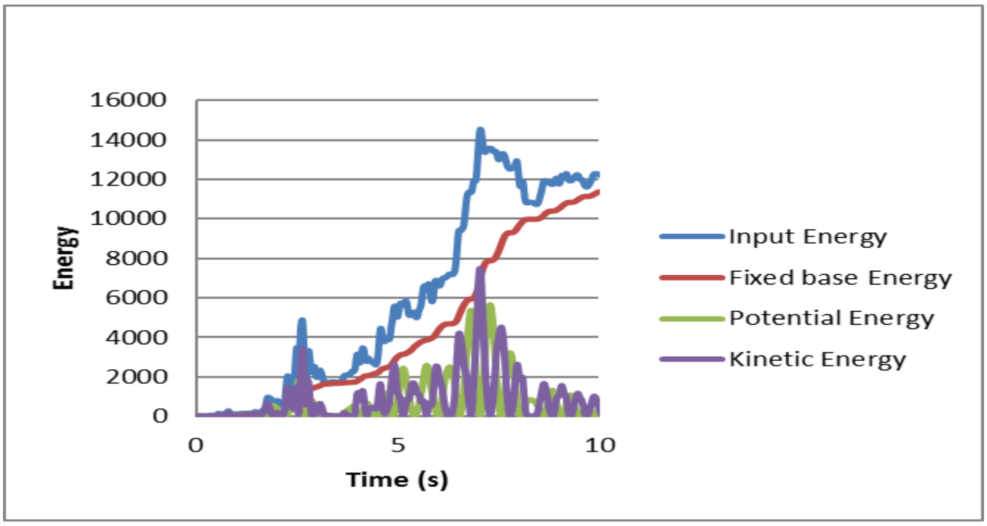
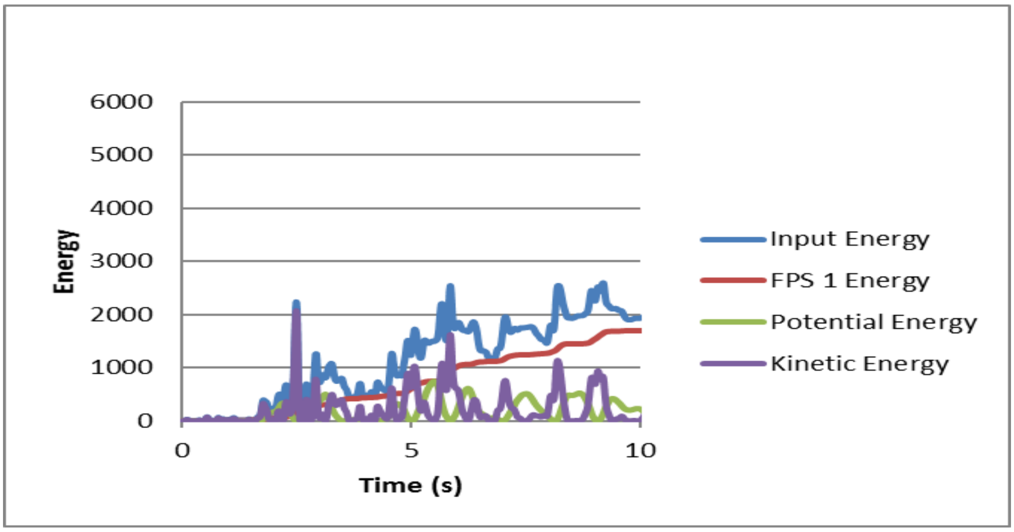
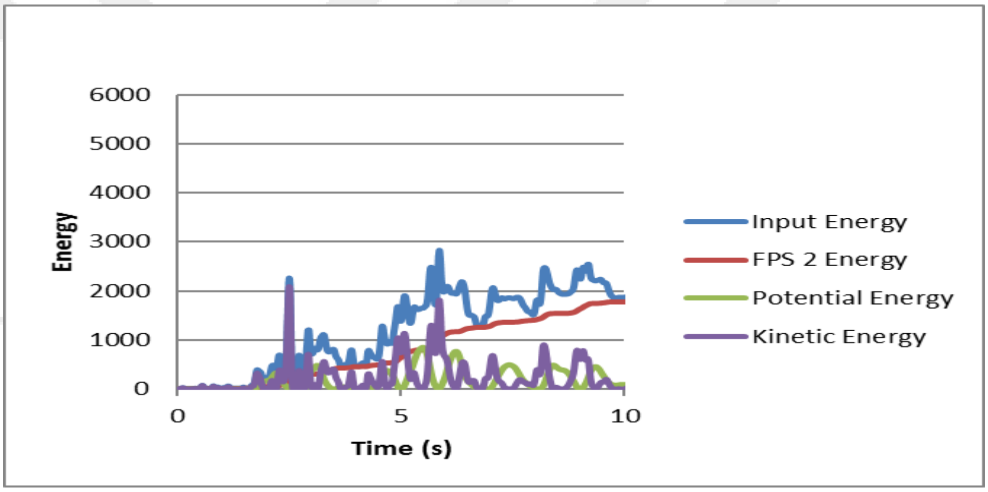


Figure 4.32 Energy within fixed base system under Corralitos earthquake



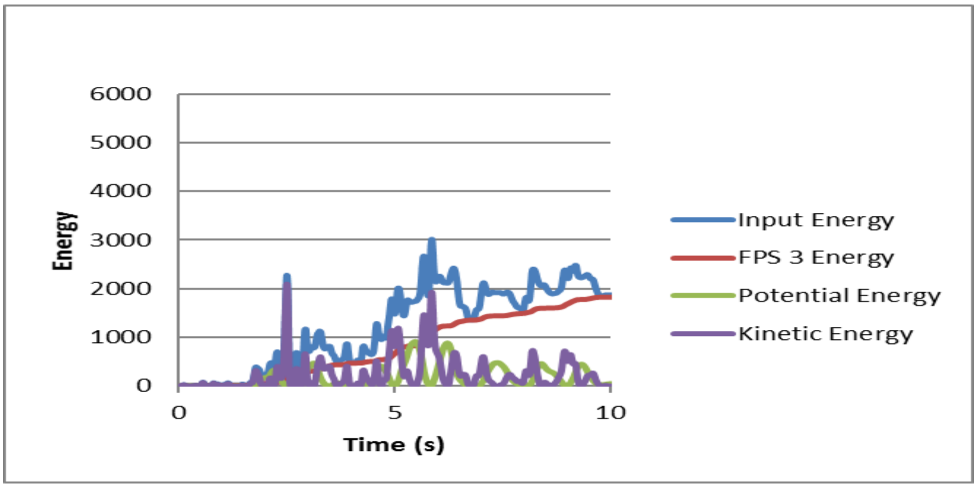
6000
5000
4000
3000
2000
1000
0
Energy
0
5
10
Time (s)
Input Energy
FPS 1 Energy
Potential Energy
Kinetic Energy

a)



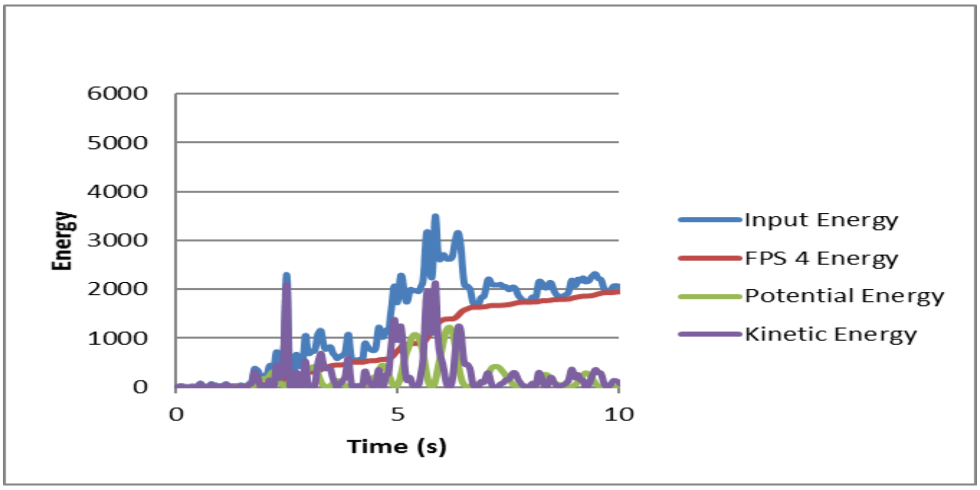
6000
5000
4000
3000
2000
1000
0
Energy
0
5
10
Time (s)
Input Energy
FPS 2 Energy
Potential Energy
Kinetic Energy

b)



6000
5000
4000
3000
2000
1000
0
Energy
0
5
10
Time (s)
Input Energy
FPS 3 Energy
Potential Energy
Kinetic Energy

c)



d)

Figure 4.33 Energy within an isolated system under Corralitos earthquake a) FPS 1, b) FPS 2, c) FPS 3, d) FPS 4

CHAPTER 5

CONCLUSIONS

This study investigated the structural performance of the existing buildings with the fixed base system and those upgraded with friction pendulum isolation systems. The performance properties were assessed based on the nonlinear dynamic time history analyses. From the results of this study, the following conclusions can be drawn:

- The analysis of the results showed that improvement of auxiliary seismic execution levels was maintained with the use of FPS.
- Lowering the coefficients of friction of the FPS seemed to be the best approach to enhance seismic execution of the structure.
- Big energy dissipation and reduced displacement to accepted level was happened due to the application of FPS.
- Significant reduction of base shear in isolated structure was found under all earthquakes.
- Relative displacements of the base isolated structure were observed to be considerably low in comparison to the fixed base structure.
- The earthquake load transmitted to the model structure was effectively reduced by using FPS type base isolation devices.
- Analysis of the results indicated that the maximum story relative displacement was also affected by increased coefficient of friction. The maximum story relative displacement of the structures with friction pendulum isolation systems was smaller than other structures with the fixed base system, by increasing the coefficient of friction, the story displacements had a tendency to increase.
- The comparison of the relative drift for the structure with a fixed base system and upgraded building with friction pendulum isolation system indicated that the latter had significantly lower drift values than the former, depending mainly on the value of coefficient of friction and earthquake acceleration used.

- It was worthy noting that the structure with a friction pendulum isolation system with less coefficient of friction were performing better than the upgraded structure with a friction pendulum isolation system with a higher coefficient of friction.

REFERENCES

Al-Hussaini, T. M., Zayas, V. A., Constantinou, M. C. (1994). Seismic isolation of multi-story frame structures using spherical isolation systems, *In Seismic Isolation of Multi-Story Frame Structures Using Spherical Isolation Systems* (pp. 153-153).

Almazan, J. L., De la Llera, J. C. (2002). Analytical model of structures with frictional pendulum isolators, *Earthquake Engineering and Structural Dynamics*, **31**, 305-332.

ASCE. (2010) – Code 7: Minimum design loads for buildings and other structures. American Society of Civil Engineers.

Becker, T. C. (2011). Advanced modeling of the performance of structures supported on triple friction pendulum bearings. Department of Civil and Environmental Engineering. Ph.D Thesis, University of California. Berkeley.

Castaldo, P., Ripani, M. (2016). Optimal design of friction pendulum system properties for isolated structures considering different soil conditions, *Soil Dynamics and Earthquake Engineering*, **90**, 74-87.

Chalhoub, M. S., Kelly, J. M. (1990). Shake table test of cylindrical water tanks in base-isolated structures, *Journal of Engineering Mechanics*, **116**, 1451-1472.

El-Bayoumi, K., Naguib, M., Salem, F. A. (2015). Dynamic analysis of high rise seismically isolated buildings, *American Journal of Civil Engineering*, **3**, 43-50.

Fadi, F., Constantinou, M. C. (2010). Evaluation of simplified methods of analysis for structures with triple friction pendulum isolators, *Earthquake Engineering and Structural Dynamics*, **39**, 5-22.

Fakhouri, M. Y., Igarashi, A. (2012). Dynamic response control of multi-story structures by isolators with multiple plane sliding surfaces, *Engineering Structures*, **34**, 81-94.

Georgios, E. S., Antonios P. L. (2015). Dynamic analysis of a friction pendulum isolation system (FPS) under earthquake excitation. Department of Production Engineering and Management. Ph.D. Thesis, Technical University. Crete.

Hacheem, Z. A., AL-Shimmari, I. K. (2010). Finite element analysis of a friction pendulum bearing base isolation system for earthquake loads, *Journal of Engineering* , **16**, 5316-5336.

Jangid, R. S. (2005). Optimum friction pendulum system for near-fault motions, *Engineering Structures*, **27**, 349-359.

Kang, B. S., Kang, G. J., Moon, B. Y. (2003). Hole and lead plug effect on fiber reinforced elastomeric isolator for seismic isolation, *Journal of Materials Processing Technology*, **140**, 592-597.

Krishnamoorthy, A., Anita, S. (2016). Soil–structure interaction analysis of a FPS-isolated structure using finite element model, *In Elsevier Structures*, **5**, 44-57

Landi, L., Grazi, G., Diotallevi, P. P. (2016). Comparison of different models for friction pendulum isolators in structures subjected to horizontal and vertical ground motions, *Soil Dynamics and Earthquake Engineering*, **81**, 75-83.

Luo, C., Walk, S. T., Gordon, D. M., Feldgarden, M., Tiedje, J. M., Konstantinidis, K. T. (2011). Genome sequencing of environmental escherichia coli expands understanding of the ecology and speciation of the model bacterial species, *Proceedings of the National Academy of Sciences*, **108**, 7200-7205.

Matsagar, V. A., Jangid, R. S. (2004). Influence of isolator characteristics on the response of base-isolated structures, *Engineering Structures*, **26**, 1735-1749.

Moeindarbari, H., Taghikhany, T. (2014). Seismic optimum design of triple friction pendulum bearing subjected to near-fault pulse-like ground motions, *Structural and Multidisciplinary Optimization*, **50**, 701-716.

Moon, B.Y, Kang, G.J., Kang, B.S., Kelly, J.M. (2002). Design and manufacturing of fiber reinforced elastomeric isolator for seismic isolation, *Journal of Materials Processing Technology* 130-131, 145-150.

Morgan, T. A., Mahin, S. A. (2010). Achieving reliable seismic performance enhancement using multi-stage friction pendulum isolators, *Earthquake Engineering and Structural Dynamics*, **39**, 1443-1461**.**

Mostaghel N, Khodaverdian M. (1987). Dynamic of resilient-friction base isolator (R-FBI), *Earthquake Engineering and Structural Dynamics*.**15**, 379-390

Naeim, F., Kelly, J. M. (1999). Design of seismic isolated structures from theory to practice. *John Wiley and Sons*, **4**, 71-83.

Nassani, D. E., Abdulmajeed, M. W. (2015). Seismic base isolation in reinforced concrete structures, *International Journal of Research Studies in Science Engineering and Technology*, **2**, 1-13.

Nikolay, K., Ryan, C., Ali, P. (2008). Development of a friction pendulum bearing base isolation system for earthquake engineering education, *In American Society for Engineering Education*, **40**, 601-617.

Özsoy, A. E., Özkaynak, H. (2017). Structural and earthquake engineering applications of a model wooden structure, *Civil Engineering and Architecture*, **5**, 18-25.

Panchal, V. R., Jangid, R. S. (2008). Variable friction pendulum system for seismic isolation of liquid storage tanks, *Nuclear Engineering and Design*, **238**, 1304-1315.

Pocanschi, A., Phocas, M. C. (2007). Earthquake isolator with progressive nonlinear deformability, *Engineering Structures*, **29**, 2586-2592.

Raftoyiannis, I. G., Michaltsos, G. T. (2016). The influence of the vertical inertia forces on the behavior of friction pendulum bearings (FPB), *Archive of Applied Mechanics*, 1-11.

Ryan, K. L., Chopra, A. K. (2004). Estimating the seismic displacement of friction pendulum isolators based on non-linear response history analysis, *Earthquake Engineering and Structural Dynamics*, **33**, 359-373.

Turer, A., Özden, B. (2008). Seismic base isolation using low-cost scrap tire pads (STP), *Materials and Structures*, **41**, 891-908.

Tsai, H. C., Kelly, J. M. (2002). Stiffness analysis of fiber-reinforced rectangular seismic isolators, *Journal of Engineering Mechanics*, **128**, 462-470.

Tsai, C. S., Lu, P. C., Chen, W. S., Chiang, T. C., Yang, C. T., Lin, Y. C. (2008). Finite element formulation and shaking table tests of direction-optimized-friction-pendulum system, *Engineering Structures*, **30**, 2321-2329.

Wipplinger, L. A. (2004). Dynamic testing of a masonry structure on a passive isolation system, *Journal of Architectural Engineering*, **10**, 15-21.

Cheng, J., Wang, Y., Huang, N. C., Wu, G., Qing, Z. Y., Sun, D. M. (2001). A computer control system for arm-driven inverted pendulum, *Electric Machines and Control*, **5**, 277-280.

Zayas, V. A., Low, S. S., Mahin, S. A. (1990). A simple pendulum technique for achieving seismic isolation, *Earthquake Spectra*, **6**, 317-333.