Application od Base Isolation as a Seismic Retrofitting Techniques

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Submitted to the
Institute of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Master of Science
in
Civil Engineering

Eastern Mediterranean University
September 2019
Gazimağusa, North Cyprus

Approval of the Institute of Graduate Studies and Research

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ABSTRACT

Seismic performance of reinforced concrete structures is indeed one of the most critical points when it comes to human life safety. For many years, scientists were trying to find a way to accurately assess the structural behavior of buildings under severe earthquake records, and to implement a way to improves the performance of the structure. This study is aiming to evaluate the seismic performance of reinforced concrete structures using two main methods which are the equivalent lateral load method and the time history analysis to assess the performance of the building and define the deficiency points. Thereafter a retrofitting strategy is planned to be handled through the applications of different types of base isolations (lead core rubber bearing, flat sliding bearing, and friction pendulum bearing) on an existed low-rise building to check the capability of the isolators to improve the building performance against earthquake records, and to check how isolators are capable of decreasing the story accelerations in the higher stories, which helps in reducing the damage of the non-structural elements. Results indicate that lead core rubber bearing isolator show the maximum reduction for the accelerations in the higher stories which reflect its outstanding performance with the respect the other considered types.

Keywords: Reinforced concrete, base isolation, time history analysis, seismic performance, lead rubber bearing isolator, sliding isolator.

ÖZ

Betonarme yapıların sismik performansı, insanların yaşam güvenliği açısından gerçekten en önemli noktalardan biridir. Uzun yıllar boyunca, bilim adamları, şiddetli deprem kayıtları altındaki binaların yapısal davranışlarını doğru bir şekilde değerlendirmek ve yapının performansını iyileştirmek için metotlar bulmak ve uygulamak için çalışmaktadırlar. Bu çalışma, betonarme yapıların sismik performansını, eşdeğer yanal yük yöntemi ve binanın performansını ve eksik noktalarını tanımlamak için zaman tanım alanında analizini kullanarak değerlendirmeyi kapsayan iki ana yöntemi kullanmayı amaçlamaktadır. Bu çalışma, betonarme yapıların sismik performansını değerlendirmek amacıyla iki temel metot olan eşdeğer deprem yükü yöntemi ve zaman tanım alanında analiz yöntemi kullanılarak binanın performansını değerlendirme ve eksik noktalarını tanımlama çalışmalarını içermektedir. Bunun yanında, binaların deprem kayıtlarına karşı performansını artırmak ve izolatörlerin kapasitelerini kontrol etmek amacıyla mevcut alçak yükseklikteki bir binada farklı tipte taban izolatör uygulamaları yoluyla bir güçlendirme stratejisi ele alınmış, ve izolatörlerin yapısal olmayan elemanların zarar görmesinin azaltılmasına yardımcı olmak ve daha yüksek katlardaki zamana bağlı hızlanmalarının nasıl azaltabildiğini kontrol etmeyi içermektedir. Yapılan analiz sonuçları, kurşun çekirdekli kauçuk izolatörünün, diğer düşünülen tiplere göre yüksek katlardaki ivmenin azaltılmasında maksimum üstün performans sergilediğini göstermiştir.

Anahtar Kelimeler: Betonarme, temel izolasyonu, zaman tanım alanında analiz, sismik performans, kurşun çekirdekli kauçuk izolatör, kayıcı izolatör

DEDICATION

To My Family…

ACKNOWLEDGMENT

I want to thank my supervisor Assoc. Prof. Dr. Mehmet Cemal Geneş for his patient, tolerant and understanding personality during this process. He was very supportive and informative at every step of this thesis. His knowledge on academic publications was very helpful and important for me. He will always be remembered as a valuable teacher and an understanding, wise friend.

I wish to express my deepest gratitude to my family and friends for their support and motivation.

I do not miss the chance to thank Civil Engineering Department of EMU for their valuable contributions on me throughout my undergraduate and graduation years.

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LIST OF SYMBOLS AND ABBREVIATIONS

μ_{max}	Maximum coefficient of friction
μ_{min}	Minimum coefficient of friction
A	Rate parameter
ASCE	American society of civil engineering
CP	Collapse prevention
DIS	Dynamic Isolation System Company
DL	Dead Load
D_y	Maximum displacement of the isolator
EDF	Electricite De France system
EERC	Earthquake engineering research center
FB	Fixed based
FSB	Flat sliding isolators
FSB H	Flat sliding isolators-high stiffness
FSB L	Flat sliding isolators-low stiffness
FSB M	Flat sliding isolators -medium stiffness
F_y	Yield force of bearing
HI	Hybrid isolation
I	Importance factor
IO	Immediate occupancy
K_d	Elastic stiffness
K_e	Post-yield stiffness of bearing

K_v	Vertical stiffness
LL	Live load
LRB-2D	Lead rubber bearing 2 diameters
LRB-H	Lead rubber bearing- high stiffness
LRBI	Lead rubber bearing isolator
LRB-L	Lead rubber bearing- low stiffness
LRB-M	Lead rubber bearing- medium stiffness
LS	Life safety
M2	Bending moment in minor axis
M3	Bending moment in major axis
MRPRA	Malaysian rubber producers research association
P	Axial load
PEER	Pacific engineering research center
PFI	Pendulum friction isolator
PGA	Peak ground accelerations
Q_d	Characteristic strength
RSF	Radius of the sliding surface
S_1	One second spectral acceleration
SBI	Sliding bearing isolator
S_s	Short spectral acceleration
TS498	Turkish code for loads
TS500	Turkish code for designing reinforced concrete element
TBSC2018	Turkey Building Seismic code (2018)
Z	Site class

Chapter 1

INTRODUCTION

1.1 General Introduction

Development of advanced computational tools, that are capable of handling complicated numerical calculations, gave the opportunity for civil engineers and scientist to come up with new techniques that have considerably impacted the construction industry by ensuring human life safety through an accurate evaluation of the structure's seismic performance under severe ground motion records based on its material and geometric nonlinearity.

These new methods were utilized to assess the seismic performance of aged structures to improve their behavior under expected shaking intensities through a retrofitting process using various types of strengthening techniques.

Although studies regarding base isolation system in the middle east region are limited, to the increase in the earthquake risk during recent years this technology has started to be considered as a solution for reducing the negative effects of such a natural disaster.

In general, base isolation system is a way to reduce the demand force on the structure by allowing its base to be more flexibly when a significant shaking intensity is applied.

1.2 Main Objective

The main objective in this study is to examine the performance of different structures seismically retrofitted using various types of base isolators. Depending on using two method, lateral load and time history analysis method to evaluate the performance of the building and indicate the deficiency points, so a strategy using retrofitting techniques is planned with the help of base isolating systems such as lead rubber bearing isolator (LRBI) and sliding bearing isolator (SBI).

1.3 Limitation of this study

Due to the lack of the obtained economical information about the base isolator's devices. This study mainly focused on the seismic performance-wise of the base isolators regardless of the economic aspects.

1.4 Content of the thesis

Chapter one objective is to provide a general introduction about the base isolation systems and the aim of using these systems.

Chapter two is a literature review on the past studies that has been applied on structure using base isolation system regarding the properties, implantations, and effect of these systems.

Chapter three will describe the methodology used, it contains the steps that have been used for modelling the building by ETABS program, defining the Non-Linear properties of the isolators, describing the Non-Linear Dynamic analysis (Time-History) method.

Chapter four will show the results of the analysis that have been done on structure using different types of base isolation systems, and discuss the results of each system in terms of acceleration, base shear, inter story drift, energy and natural period, and finally make a comparison for all these results between all the types of base isolation systems to see the more suitable and fitting result.

Chapter five will conclude the thesis report and summarize the data obtained from the models' analysis, in addition in this chapter recommendation for future studies are proposed.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

In this chapter a review will be given regarding the base isolation history and its development through the years and give a brief explanation about the types of seismic isolation bearings and systems applied on the structures as a retrofitting technique.

2.2 Historical Development of Base Isolations

In 1976 the earthquake engineering research center (EERC) also known as pacific engineering research center (PEER) of California's university at Berkley, was the first institution to apply studies about the feasibility by using raw rubber elastomeric bearing as a base isolator to protect buildings form earthquakes. The study that had been carried out was a joined work between the EERC and the Malaysian rubber producers research association (MRPRA) the study had been funded by the MRPRA, the national science foundation, and the electric power institute. The study program began with a simple model for a building consist of three stories and a handmade bearing produced from a low-cost rubber. Trials using shaking tables had been applied on the model, where these trials showed that the use of isolators bearings could reduce the acceleration by a factor up to 10 in equivalence to conservative design. This study proved that the model reacts as stiff body and the isolation system absorbs all the twists, which this province has opened the door for more studies where practical combinations of rubber was used (Derham et al.1978).

A study for a five-story, three bays, and 40-ton model had been used to study the base isolation. This study carried out using five tests showing that the isolation achieved through rubber bearings which had the ability to significantly reduce the increase in speed felt by the structure itself. In addition, this study proved that the use of additional elements such as lead plugs in the bearings or energy absorbing devices made of steel in the isolation system will increase the amount of damping which reduce the ability of the isolation system to decrease the acceleration felt by the internal equipment's. This study was aimed for finding a well-organized way of adding damping to the rubber bearing and not as a disconnected element supplemented to the isolation system (Kelly and Hodder,1981).

Then, a shaking table testing system has continued at the University of New York at buffalo's national center for earthquake engineering research. The evaluations tests of base isolators were applied on six-story frame structure (AL-Hussaini et al. 1994).

After all these studies and tests, researchers did not stop at that, and they start to create new concepts regarding the base isolation systems, a lot of these concepts have achieved a successful validation through the use of the shaking table test like:

- Friction pendulum isolator
- Almost lifted structure concept
- Core suspended isolation system
- Rolling ball isolation
- Elastomeric isolator

2.3 Types of Seismic Isolation Bearing

A variety of seismic isolation bearing for seismic protection of structure have been designed and deployed around the world. A brief explanation of the basic characteristic, mechanical behavior, and analytical modeling for each type of bearing is described in this section.

2.3.1 Laminated Rubber Bearings (Elastomeric Bearings)

Elastomeric bearings consist of rotating natural or synthetic layers of rubber bonded to steel plates placed around a lead core as shown in Figure 1 where:

- Rubber layers provide flexibility
- Steel plates provide vertical stiffness to support building weight
- Lead plug provide a source of energy dissipation

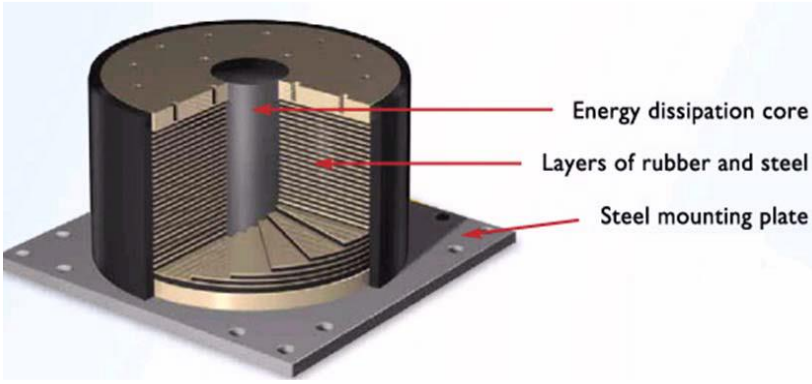

Figure 1: LRBI (DIS Company)

The main application of these bearings is for bridges and superstructures, which are frequently subjected to significant dimensional and shape changes due to temperature changes. The successes of this system made it extend to be applied on buildings and other structures, where these bearings are designed to support large weights while offering little resistance to large horizontal displacement. This system works as the load capacity is increased by reducing the thickness of each rubber, and the resistance to horizontal and tilting movements is reduced by increasing the total height of the rubber (Warn and Ryan, 2012) (Robinson 1982) (Jivrajani 2017).

Elastomeric bearings can be applied without the use of the lead core in two methods: low- damping and high-damping natural rubber (Matsagar and Jangid, 2008).

Low-damping rubber

- Provide a linear shear stress-strain behavior up to and exceed 100%
- Provide an equivalent damping ratio between 2% and 3%
- Easy to be manufactured and modeled
- Has a weak sensitivity to temperature, ageing, and loading rate
- Supplemental damping system such as yielding steel bars should be used

High-damping rubber

- Provide an equivalent damping ratio from 10% to 20% at 100% shear-strain
- Provide a shear modulus like low-damping of 345 to 1380 KPa
- The level of damping increased by adding carbon black and other fillers to the rubber during the mixing procedure

Figure 2: Rubber bearing isolator with low or high damping rubber (DIS Company)

2.3.2 Sliding Bearings Isolators (SBI)

These types of bearings support the structure weight on a bearing that placed on a Teflon sliding interface, where this interface has engineered with a low friction coefficient to limit the resistance to horizontal forces. The bearing at the sliding interface composed of polytetrafluorethylene material and stainless steel as shown in Figure 3, (Warn and Ryan, 2012) (Mokha et al. 1990).

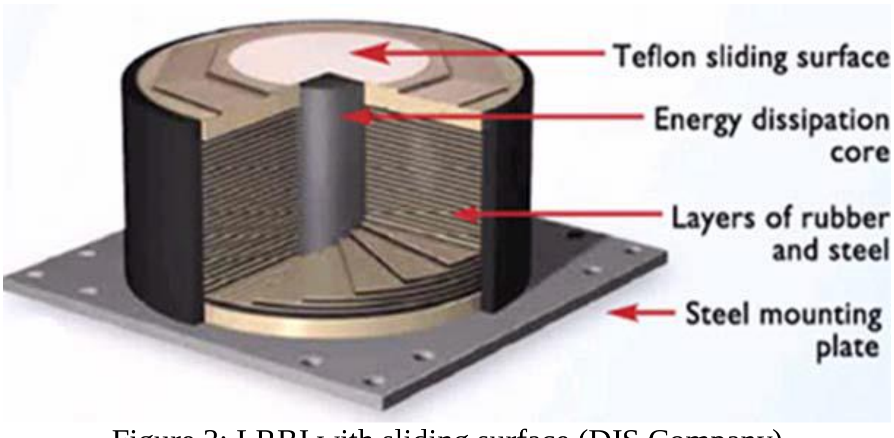

Figure 3: LRBI with sliding surface (DIS Company)

There are different types and methods of applications for the SBI, and the most widely used types are:

- Pure friction system
- Spherical friction pendulum bearing system
- Resilient-friction base isolator
- Electricite De France system
- Variable friction pendulum system

These methods will be explained briefly in section 2.4.

2.3.3 Hybrid Base Isolation

This an adopted system where is used as combination between the rubber and sliding bearing isolators. This system has more effectiveness that the conventional rubber bearing system where it provides more elongation of equivalent natural period and achieving more absorption of response energy (Kawamura et al. 2000); (Oliveto et al. 2014); (Markou et al. 2018).

2.3.4 Pure Friction System (Flat sliding bearings)

Friction force is a natural and effective mechanism for energy dissipation in which will allow to reduce the acceleration effecting the structure during the earthquake. This is the simplest system of base isolation systems of all where the isolation mechanism is the sliding friction and it usually combines with other bearings or used as a joint base as shown in and Figure 4 (Jivrajani 2017); (Gu et al. 2015).

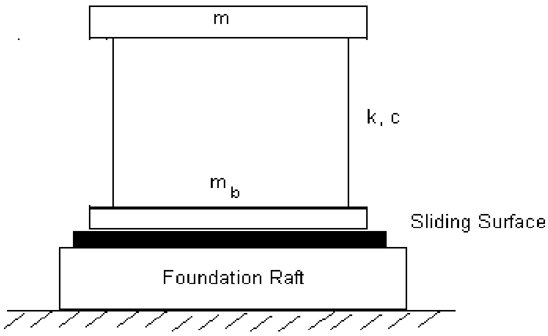

Figure 4: Diagram of pure friction base isolator (Jivrajani 2017)

2.3.5 Spherical Friction Pendulum Bearing System (PFI)

This isolator has the same properties as the pure friction isolator. However, the friction pendulum bearing consists of a horizontal sliding rest on a sphere that slide on a concave sliding surface as shown in Figure 5, however it may force a large residual displacement which they are difficult to incorporate into the structure design (Zayas et al. 1990); (Rabiei and Khoshnoudian, 2011); (Arathy and Manju, 2016).

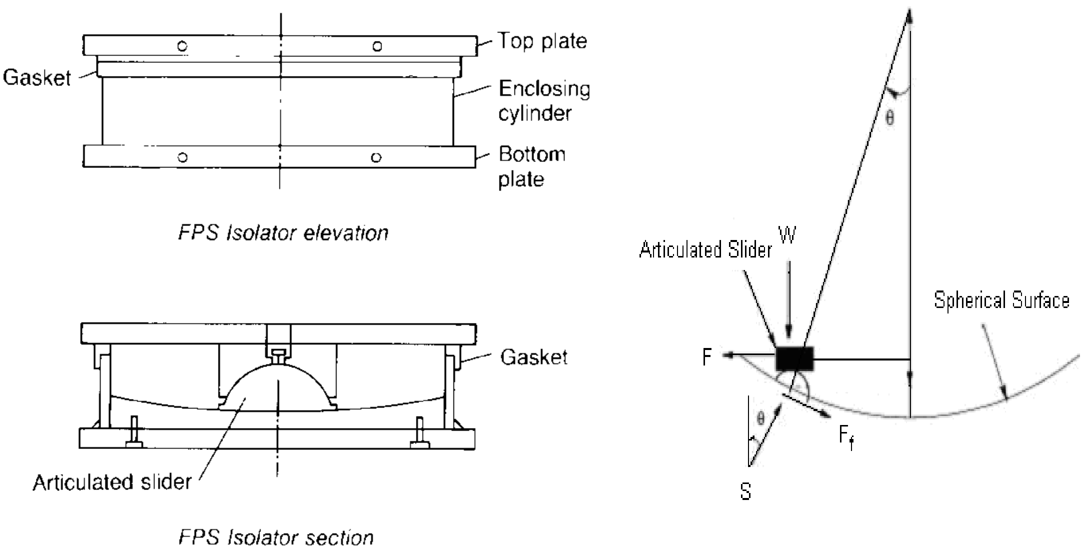

Figure 5: PFI Isolator Section (Jivrajani 2017)

2.3.6 Resilient-Friction Base Isolator System (R-FBI)

This system consisting of layers of rubber-core with sliding elements. These elements are composed of flat rings that can slide with the central rubber core on each other. In addition to a very flexible rubber cover that protects the rings against corrosion and dust. These sliding are covered with Teflon to reduce the friction, and the rubber core mentioned before helps to control the relative displacement and provide the restoring force for the system. The system work so that the sliding bearings carry the entire vertical load and the rubber core do not carry any vertical load. Figure 6 show the section of this system (Mostaghel and Khodaverdian,1987); (Jivrajani 2017).

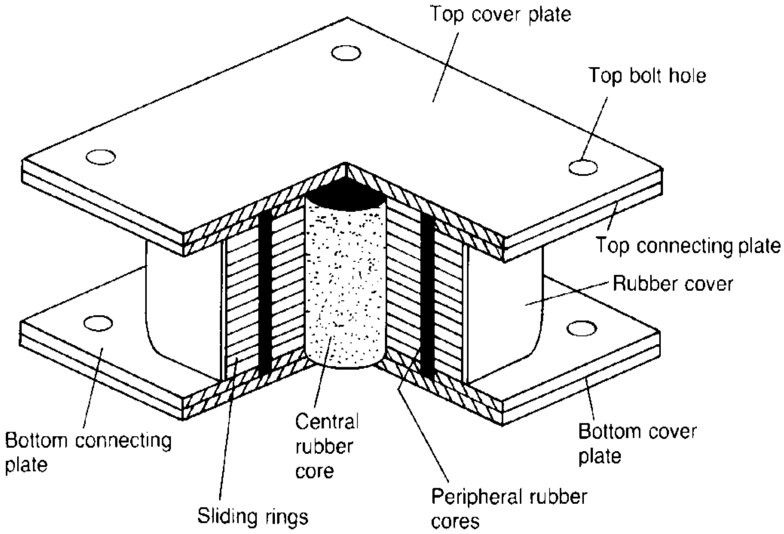

Figure 6: Resilient-Friction base isolator section (Jivrajani 2017)

2.3.7 Electricite De France system (EDF)

This and advanced system where it's a combination between the pure friction and the laminated rubber bearings, where the EDF system is one of the systems that use friction force as dissipation of the energy and Sliding elastomeric pads are used. This system work on isolating the foundation where the foundation will be constructed using a double raft system in where the sliding elastomeric bearing will be placed between the two rafts. Each pad is made of elastomeric Bloch reinforced with steel plates as shown in Figure 7. Theses pads have a high vertical stiffeners and load carrying capacity along with low stiffness to horizontal shear force. The pads will be casted with the concrete slab using stud anchors before the deployment in the field (Guiraud et al. 1985); (Jivrajani 2017).

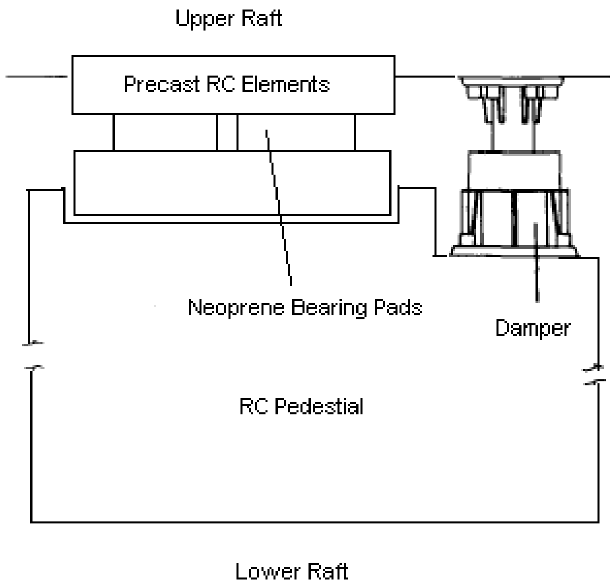

Figure 7: De France Isolator Section (Jivrajani 2017)

2.3.8 Variable Friction Pendulum System (VFPS)

This system is somehow a derivative of the friction pendulum system where it has a similar structure and mechanism except the friction coefficient of the sliding surface, where it varies as per the curve. This system gives the isolator an initial softness then provides a stiffness for tremors and finally become soft again to withstand a strong motion ground (Panchal and Jangid, 2009).

2.4 Installation of Base Isolation in Seismic Retrofitting

Before installing the base isolation as a retrofit scheme, a retrofitting strategy should be considered like:

- Assessments of the existing building's dynamic properties using vibration tests
- Numerical analysis needed to achieve a significant choice about the location of the base isolator and which isolation system should be used

The installation of base isolation differs depending on the structure type, so each type has its own method to be retrofitted as mentioned below.

2.4.1 Masonry Structure

While the seismic isolators are being imbedding, an under pinning is done to give a momentary support along the masonry wall. Holes are made in the wall and with an exact distance a needle beam put-on the isolator is constructed below the masonry wall as shown in Figure 8. Then the momentary support will be removed allowing the vertical load of the structure to be transferred towards the foundation through the needle beam and the isolator (Matsagar and Jangid, 2008).

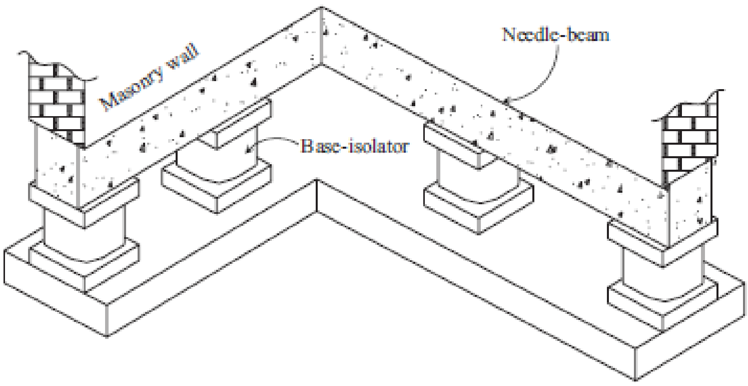

Figure 8: Load bearing masonry structure (Matsagar and Jangid, 2008)

2.4.2 Framed Structure

Framed structure is a structure consisting of beams and columns, In framed structure case the column near the foundation junction will be cut using mechanical cutter and the base isolator will be placed as shown in Figure 9. During cutting the column a temporary structure will be used to transfer the load from the superstructure to the substructure, Briefly the main concept of this temporary structure is to transfer the load from the column to two hydraulic jacks. Cut the column then placed the isolator, so when the hydraulic jacks are removed the load will be transferred from the jacks to the isolator (Clemente et al. 2012); (Matsagar and Jangid, 2008).

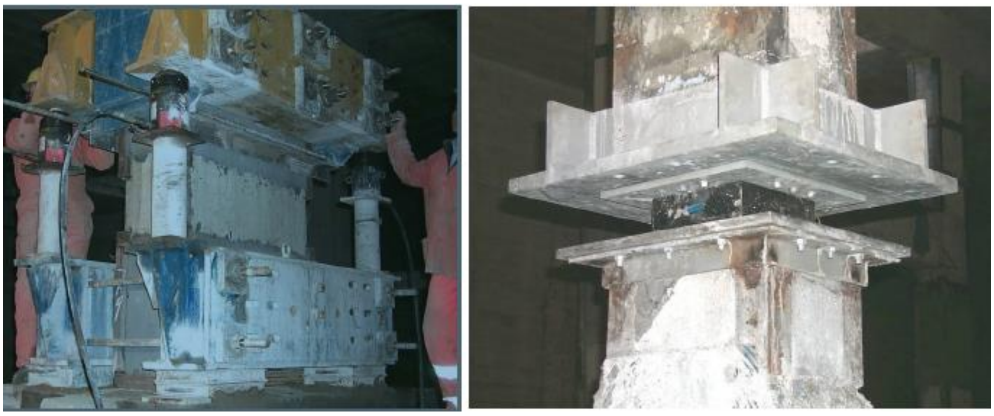
Figure 9: Column before and after the installation of the isolator (Clemente et al. 2012)

2.5 Previous Work Done in The Field of Base Isolation

Su et al. (1991): In this study the authors discussed the analysis on a new combination of base isolator obtained after combining the properties of electricity de France (EDF) base isolator and resilient base isolator (R-FB1) device, and new isolator formed which named sliding resilient base isolation system (SR-F). For these isolator spectra, a curve is generated and compared with that which is generated for EDF and R-FB1 isolator system. Whatever results are received, they are compared with fixed base system for various conditions and various earthquake records. Base shear, spectral acceleration, and spectral displacement are found. The obtained results from these different earthquake records were then compared with SR-F system which is proposed as an isolator by Su et al (1991). Peak response of all earthquakes for EDF and R-FB1 were recorded and the obtained results are compared with the SR-F system. Therefore, maximum responses almost ended without large base displacement and the peak response of this isolator was also considerably serious in frequency and amplitude content.

Shenton and Lin (1993): In this study, the authors compared and analyzed relative results of fix based and base isolated structure. Referring the structural agencies Association of California (SEAOC), the reinforced concrete fix base structure was designed, and it is compared with a fixed base response. According to the SEAOC recommendation, the base shear was varying. Three various type of time history, post-earthquake records were selected to perform nonlinear dynamic analysis for fixed base and base isolated structure. Results were compared to 25% and 50% of the specified lateral force by SEAOC and the performance of building was checked for various lateral forces.

Concellara et al. (2013): In this study, the authors described the difference between lead rubber isolator and friction slider. Isolator was composed of lead rubber bearing in combination with friction slider (FS) and was named as high damping hybrid seismic isolator. The seismic response of high damping hybrid seismic isolator was the difference with lead rubber isolator response. Under different seismic activity in the form of frequency and intensity, the same structure was examined. The paper is basically a composite centered on HDSI, compared to lead rubber isolator. Various seismic activities were considered, and results were compared as in the form of base shear, shear force, displacement at the base of the super structure. The comparative result shows HDHSI gives superior safety for severe seismic activity than other.

Li and Li (2014): In this study, the authors showed the obtained results about base isolator with variable stiffness and damping, modeling design and experimental testing of the new isolator. Sometimes the impact of earthquakes is so serious that the passive nature of rubber is not able to generate energy due to seismic region, so smart base isolation with adaptive and controllable properties was developed with different stiffness and damping properties of the isolator. This paper describes that the design and experimental testing, dynamic modeling of smart rubber.

Sekar and Kadappan (2015): The authors showed about the comparison of base isolated bearing and rigid base reinforced concrete building with the effect of soil, earthquake zone and on normal as well as sloping ground. For this study, they have taken a multistoried RC building with normal and sloping ground surface and designed it with and without an isolator. Different story height ranges from 1 to 10 were taken with different seismic zones, and the plan of the building was rectangular having size 12x16m along with seismic zone. Dynamic linear analysis has been performed by using response spectrum method. The different results were obtained with the different condition of terrain and zone. As with the introduction of the isolator, the fundamental natural time period of structure increases but base shear reduces. And the Enter- story drift of the building also increases. As due to different terrain condition results were going to change as base isolator make the building as rigid building with the higher time period.

Concellara et al. (2017): Donate Cancellara and his colleagues carried out experimental work on two base isolation systems with RC multistoried building according to the European code. The study is based on plan irregularity and hence irregular plan was chosen for it. The comparison is done, and inferences are drawn on high damping rubber bearing (HDRB) in parallel to friction bearing and lead rubber isolator laid in parallel with friction slider. Results are recorded according to accelerogram with ground motion acceleration. Time history analysis was taken out and results were compared. The comparison was done based on response and behavior of normal rigid base building with an isolated building.

Markou et al. (2016): The authors presented their paper on hybrid base isolation system under earthquake excitation. Two building were taken for the study to find out the governing parameters, features or physical properties of hybrid base isolation system. The building was isolated in salarino Sicily in Italy. Optimization techniques has been used for isolator property design. A high damping rubber bearing systems has been used, and the bearing's mathematical model was generated in two different types bilinear model and trilinear model. Also, a friction slides bearing system is used, special column model was prepared for hybrid base isolation system and different analytical models were checked for different earthquake forces and acceleration by using Time History Analysis. The result was found out to focus on the performance of the hybrid bearing system for different earthquake vulnerability and different location and type.

Darshale and Shelke (2016): The authors investigated the response of the base isolated structure to show that base isolation is one of the system types for energy dissipation. It is a passive system of energy control. Isolator basically isolates the superstructure and foundation and it partially reflects and partially absorb the energy. Due to the introduction of lead rubber isolator, the horizontal movement of the building increases i.e. fundamental natural time period increase and horizontal stiffness of building decreases. The inner story drift after introduction of isolator is reduced up to certain level. G+14 regular RC building is taken into the study for comparison of rigid base and base isolated structure. The fundamental natural time period of the structure is approximately 1.7sec where in for isolated structure is 4.3sec. As the natural time period increases the energy dissipation also increases and response reduces. Due to isolation inner story drift, base shear acceleration is reduced.

2.6 Applications of Base Isolation (Case Studies)

2.6.1 Oakland City Hall Retrofit Project (Walters et a1. 1995)

Oakland City Hall was Built in 1914.It has a full basement. a 3-story podium, a l0-story office tower, and a 2-story base for the clock tower, and a 26.5 m Hight. The structure of the building is a riveted steel frame with infill masonry walls of brick, granite, and terra cotta. Due to the extensive damage from the 1989 Loma Prieta earthquake, this building had been closed since the earthquake. The interior of the building consists of the city council chambers and the city offices. Because the building is listed on the historic register, any retrofit strategy would require preserving the interior architecture and the historic fabric. After extensive studies, it was concluded that seismic isolation retrofit was the best solution. The original building had a period of around 2 sec, and it is located 5 km from the Hayward fault. The building has been assessed by seismologists to have a 44% probability of producing an earthquake with a magnitude M = 7 on the northern segment of the Hayward fault within the next 30 years. Thereby mitigating damage to brittle infill and historic finishes, and stiffening elements were applied to the tower and coupled to horizontal trusses in the basement to transfer the shear forces to the isolation system. This strategy has reduced the fixed-base period of the building to 1.3 sec. The isolation system uses a combination of 36 lead-rubber bearings and 75 ordinary rubber bearings. The bearings range from 737 mm to 940 mm in diameter and are 445 mm tall. A moat was constructed around the building to provide a seismic gap of 508 mm. The installation of these isolators was a very complicated process and required shoring up of the columns, cutting the columns, and transfer the column loads to a temporary support. In order to protect the interior, the columns were raised not more than one-tenth of a 2.54 cm during the jacking process.

2.6.2 Traffic Management Center, Kearny Mesa, California (Walters et a1. 1995)

Emergency control centers are examples of essential facilities where these types of buildings should have remained functional during and after a major earthquake. Such buildings are not designed according to the provisions of the Uniform Building Code, therefor these buildings are designed with performance based on the requirements that are like those applied for hospitals. It is not surprising that emergency centers are seismically isolated because isolated buildings are less expensive to build than conventional buildings, when compared on a performance-based assessment. Example of an isolated emergency center is the construction of a 2-story Traffic Management Center for Caltrans in Kearny Mesa, California near San Diego. The superstructure has a steel frame with concentrically-braced panels at the perimeter and the isolation system has 40 high damping natural rubber. The isolators provided by Bridgestone Rubber company in Japan. The isolators are 600 mm in diameter, the nominal isolation period is around 2.5 sec, and the maximum credible isolator displacement is around 254 mm. The design base shear for the superstructure is around 15% of the structural weight. The expected inter-story drift at the Maximum Considered Earthquake (MCE) is not expected to exceed 0.1 %, where it implies that there will be very little non-structural damage even at the MCE. Because the isolators were tested to a shear strain of 280% before delivery (with an MCE strain of less than 100%), The isolators are unlikely to be damaged in the event of an earthquake of unanticipated magnitude. In addition, there is no moat around the structure and no walls, therefore there is no possibility of an impact on the superstructure in such an earthquake. Thus, eliminating the possibility of high floor accelerations that could affect sensitive equipment's.

2.6.3 Response of LAC/use Hospital in 1994 Northridge Earthquake (Kelly 1996)

Many of the base-isolated buildings in southern California have experienced earthquakes, but the with exception of the University of Southern California hospital in Los Angeles in the 1994 Northridge earthquake, the ground motions have been small. In the Northridge earthquake, the free-field peak ground acceleration was 0.49g, and in the basement under the isolation system the peak acceleration was 0.37g. Throughout the structure, the floor accelerations were in the range of 0.10 to 0.13g, with an acceleration of 0.22g on the roof of a penthouse at the sixth-story level. The maximum displacements of the isolators were around 2.5 cm, and the period of major response was around l.5 seconds. The design displacement for the system is around 40 cm at a period of 2.5 seconds. Some nearby buildings in this hospital complex were very badly damaged and had to be closed. This represents a degree of success for the isolation approach and has led to an increase in the number of projects being considered for isolation.

2.7 Nonlinear Response History Analysis

Structural engineers often design their structures such that the yield strength of the structural elements is not exceeded. However, under sever seismic activity the internal stress may exceeds the yielding stress of the structure material which inquires nonlinear analysis such as time history analysis to accommodate the real behavior of the structure. The magnitude, frequency and duration of earthquake records are the main parameters that characterize the ground motion. The mechanism behind the energy release due to the vicinity along the interface of the fault, the geological path at which the energy is transmitted, the distance from the epicenter, the focal altitude and the soil site class at the record center (Clough et al. 1993). The nature of an earthquake is unique which makes it difficult task to select the appropriate records. For this purpose, the seismic response of a structure is obtained using statistical methods where multiple records are considered and either maximum or average results are selected, since the selection of the ground motion records dramatically influence the analysis results (Seneviratna 1995).

2.7.1 Scaling of The Ground Motion Records

Design codes requires scaling for the selected ground motion records with respect to the considered earthquake spectrum. Mainly the ground motion records are scaled by frequency or time domain methods.

Scaling in Frequency Domain

It is the simplest method. However, it doesn't always converge to a solution. Not to mention the fact that this method varies the time of the records where the records lose its time characteristics. Hence, matching the record with the design spectrum yields higher energy compared with the other methods. This method basically depends on the ratio of the design spectrum to a response made of time series to maintain the motion of the Fourier phase constant (Chopra et al. 2000).

Scaling in Time Domain

This method presents a better alternative for matching the ground motion records with the design spectrum. Since it maintains the original frequency of the ground motion records. The method basically depends on adjusting the acceleration of the records by adding wavelets which have positive and negative magnitudes (Chopra et al. 2000).

2.7.2 Solution of The Nonlinear Time History

The solution of the nonlinear time history depends on the general equation of motions. The only limiting factors is the method used for obtaining the modal shape which are listed below:

Eigenvector Method

Eigenvector analysis is used to evaluate the undamped modal shape and natural frequencies under free vibration. The optimum application of eigenvector is to evaluate the dynamic response of structure under horizontal ground motions. However, residuals mass modes should be considered under high frequency. The number of modes dramatically affect the analysis results. For this purpose, mass participation factor is used to verify whether the number of modes is enough or not (Chopra et al. 2000).

Ritz Vector Method

This method depends on the driving force which makes it suitable for analysis regarding vertical motions and fast nonlinear analysis method. However, Ritz method is also widely used for analysis of horizontal ground motion. This method results in higher participation factor which increase the speed of the analysis while maintaining its accuracy (Chopra et al. 2000).

Chapter 3

RESEARCH METHODOLOGY

3.1 Introduction

This chapter illustrates the selected case study geometry and the modeling of the reinforced concrete structural buildings and present the properties of the selected base isolator devices.

3.2 Research Strategy

The aim of this study is to investigate the role of selected base isolator devices including lead rubber and sliding isolator on the seismic behavior of reinforced concrete moment framed building. In order to meet this objective 4 story reinforced concrete building with regular plan is designed to withstand only the gravity loads then equipped with the base isolating devices for assessing its seismic performance under both linear and nonlinear devices. Figure 10 briefly summarized the research strategy in flow chart form.

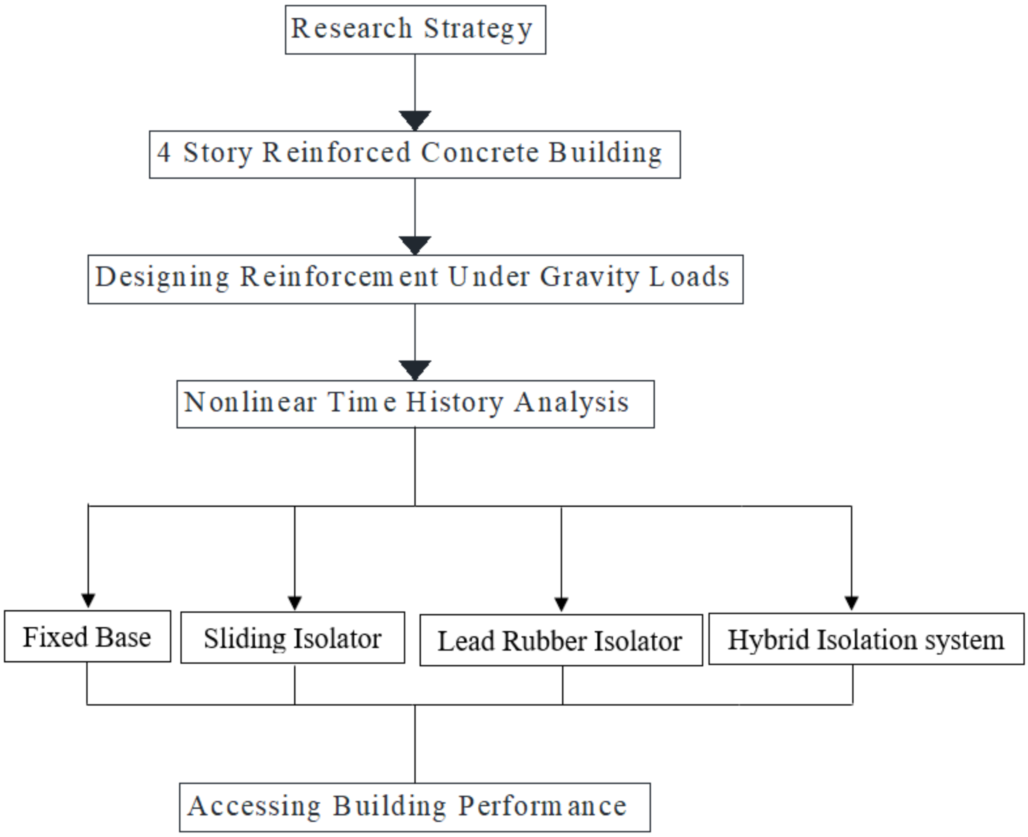

Figure 10: Flow chart of the research strategy

3.3 Assumed Location of The Case Study

The location of the reinforced concrete structural building is assumed to be located at the center of DUZCE city which is positioned to the south of the black sea in Turkey and characterized with high seismic activity and large peak ground acceleration (PGA = 0.924). The selected location is presented in Figure 11.

Figure 11: the selected location of the case study (Bing maps 2019).

3.4 Preparing the Reinforced Concrete Building for Structural Investigations

The building is basically a 4-story regular reinforced concrete moment resistant frame spanning 6 meters in both orthogonal directions. Both typical story and ground story height is 3 meters. The columns layout and side view representation of the building is presented in Figure 12 and Figure 13 respectively. The reinforcement details of the structural elements, presented in the following sections, where prepared by designing the building under the applications of gravity loads only aiming to simulate a case study of an old structure designed with deficiencies so it requires retrofitting. Thereafter, the building (fixed base) with the selected reinforcements were rechecked under the applications of static lateral load using TS489 load combinations to confirm that there is a failure in the columns and to check the needs for retrofitting. Finally, time history analysis was applied to compare the performance of the retrofitted models and the normal ones.

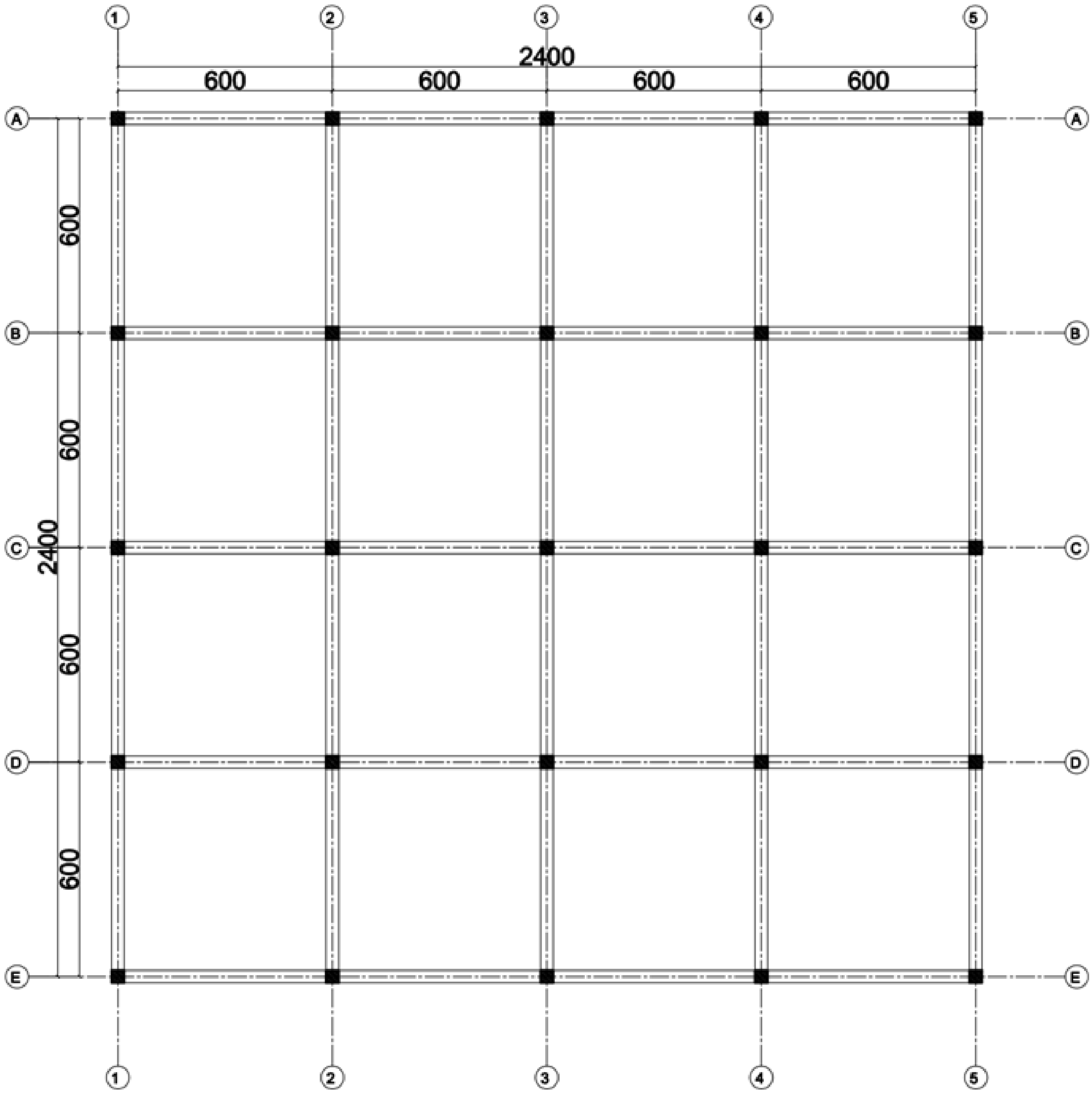

Figure 12: Column and beam layout of the selected case study.

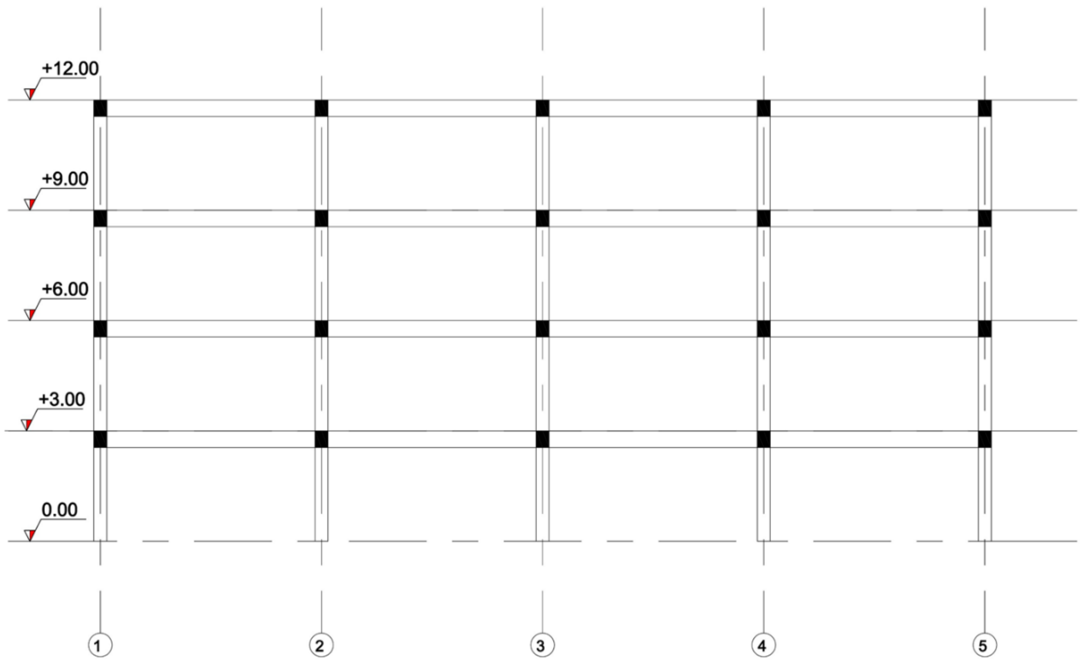

Figure 13: Elevation view of the selected case study

3.5 Building Material and Cross-Sections

The selected concrete compressive strength is taken as C30 and the steel grade is S420. The purpose of selecting these materials is to yield small cross-sections and light weight structure to facilitate the study of the base isolator's effects.

3.5.1 Column Cross-Section

The columns have a rectangular reinforced concrete cross-section with 35 cm side dimension. The main longitudinal reinforcement is selected as $8\phi20$ and the transverse reinforcement is $\phi8/20$. The moment of inertia along both major and minor axis is reduced by 20% as suggested by TS500. The columns plan, and elevation is provided in Figure 14.

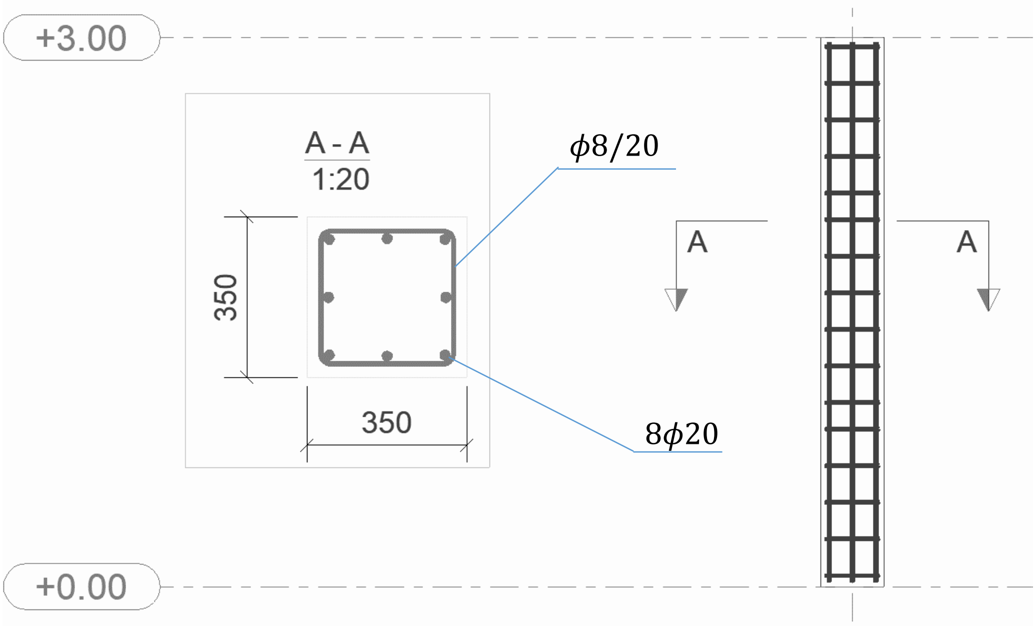

Figure 14: Selected column cross-section and reinforcement.

3.5.2 Beam Cross-Section

The beams within the selected case study have a rectangular cross-section with a depth of 45 cm and width of 35 cm. The beam moment of inertia along the major axis is reduced by 60% to simulate the crack sections. Typical representation of the Beam cross-section is presented in as an example in Figure 15 and in details in appendix V.

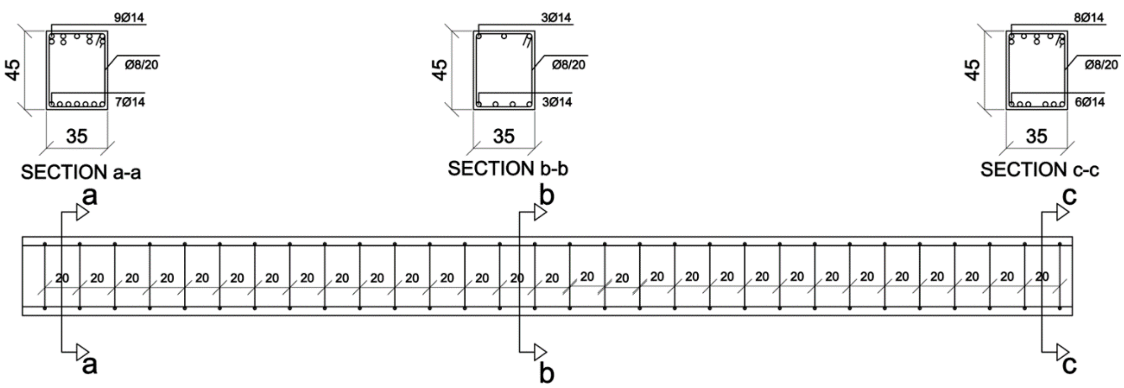

Figure 15: Selected beam cross-section and typical reinforcement.

3.5.3 Slab Cross-Section

The selected reinforced concrete slab is a two-way solid slab with a constant depth of 15 cm with no openings, in order to simulate a rigid diaphragm that can fully transfer the lateral loads to the structural elements.

3.5.4 Isolator Stiffness Categories

Three main classes for each type of isolating system is going to be used. These categories are based on the value of stiffness to be defined for the isolator as follow:

- Low stiffness: represents an isolator with a stiffness close to the minimum allowed value.
- Medium stiffness: represents an isolator with a stiffness close to the average of the minimum and maximum allowed values.
- High stiffness: represents an isolator with a stiffness close to the maximum allowed value.

These ranges of stiffness (Ke) will be presented in following sections 3.5.5, 3.5.6, and 3.5.7.

3.5.5 Lead Rubber Bearing Isolator

The reinforced concrete building is retrofitted using LRB isolator system, where it is modeled as spring element and attached to the base of the column after their fixities is released. The post yield stiffness of the base isolator is selected based on trial and error approach for each of the three predefined categories in addition to another one based on a combination of two diameters of LRB, so it yields no collapse prevention hinges after the conduction of the nonlinear history analysis. The properties of the LRB isolator are collected from Dynamic Isolation System Company (DIS) and presented in Table 1 and the following equations

Lead rubber bearing are always designed as bilinear elements (Naeim, & Kelly 1999) UBC-97, with their characteristics based on three parameters K_d, K_e, and Q_d. Where K_e can be accurately estimated from the shear modulus of the rubber tested and the bearing design. For the characteristic's strength (Q_d) it's the intercept of the hysteresis loop and the force axes as shown in Figure 16 and Figure 17. For the damping (β) and the effective stiffness (K_{eff}) it can be calculated from:

$$\beta = \frac{Area\ of\ the\ husteresis\ loop}{2\pi\ Keff\ Dy\hat{2}}$$

$$Keff = Ke + \frac{Qd}{Dy}$$

Table 1: Properties of the selected lead rubber bearing isolator.

Properties	**Explanation**	**Magnitude**	**Unit**
Q_d	Characteristic strength	0-110	KN
K_d	Elastic stiffness	200-1200	MPa
K_e	Post-yield stiffness of bearing $K_e = 10 * K_d$	2000-12000	MPa
K_v	Vertical stiffness	700000	MPa
D_y	Max displacement $D_y = \frac{Q_d}{K_e - K_d}$	0.41	Meter
F_y	Yield force of bearing $F_y = K_e * D_y$	100	KN
Post yield	K_d/K_e	0.1	-

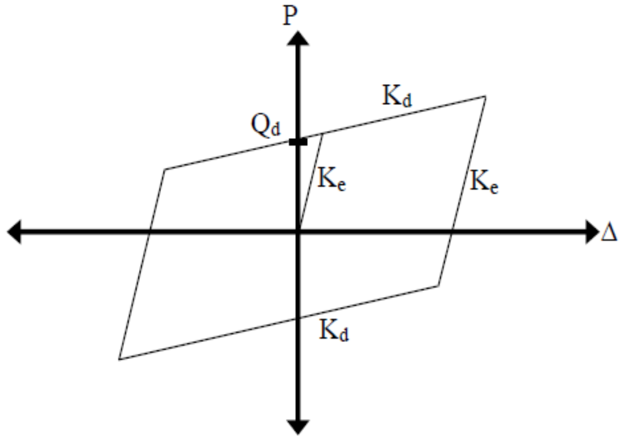

Figure 16: Complete hysteresis loop of idealized LRB bilinear behavior (DIS Company)

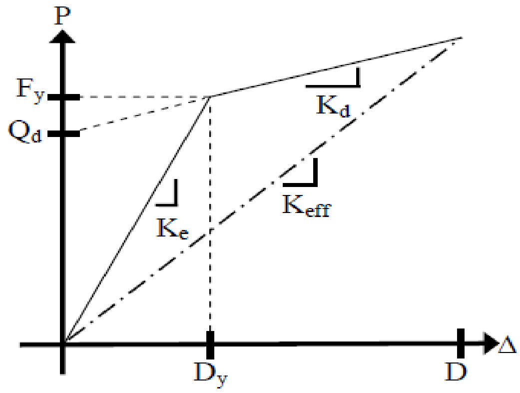

Figure 17: Force-displacement backbone curve (DIS Company)

3.5.6 Flat Sliding Bearing Isolator

The reinforced concrete building is retrofitted using sliding bearing isolator system, where it is modeled as spring element and attached to the base of the column after their fixities is released. The elastomeric backing stiffness of the base isolator is selected based on trial and error approach and designed the same as in section 3.5.5 and the hysteresis behavior will be shown in Figure 18 and Figure 19, so it yields no collapse prevention hinges after the conduction of the nonlinear time history analysis. The properties of the sliding bearing isolator are collected from DIS and presented in Table 2.

Flat sliding bearings are always designed as elaso-plastic elements (Naeim, & Kelly 1999) UBC-97 with their characteristics based on the parameters shown in Table 2. Where K_e can be accurately estimated from the shear modulus of the rubber tested and the bearing design. For the coefficient of friction Figure 20 show the curve for selecting the maximum and minimum coefficient of friction required for designing the isolator. Radius of sliding surface is represented by large number to indicate the isolator's Teflon flat surface.

Table 2: Properties of the selected flat sliding bearing isolator.

Properties	**Explanation**	**Magnitude**	**Unit**
K_d	Elastic stiffness	500-.3500	MPa
Ke	Post-yield stiffness of bearing $K_e = 10 * K_d$	5000-35000	MPa
K_v	Vertical stiffness	700000	MPa
μ_{max}	Max coefficient of friction	0.1	Unitless
μ_{min}	Min coefficient of friction	0.04	Unitless
A	Rate parameter	1	Meter
RSF	Radius of the sliding surface	10000	m/s

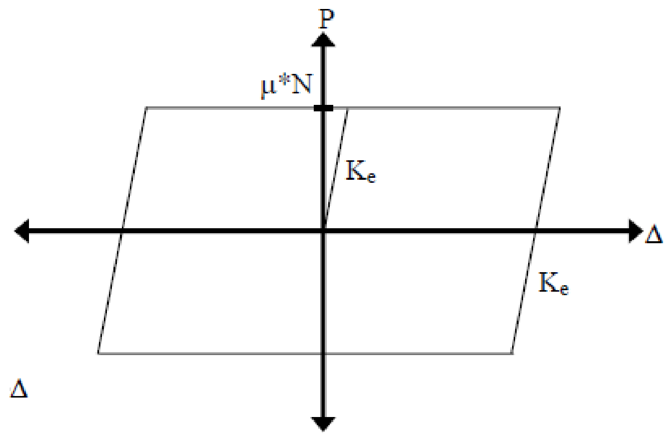

Figure 18: Complete hysteresis loop of idealized -FSB elasto-plastic behavior.

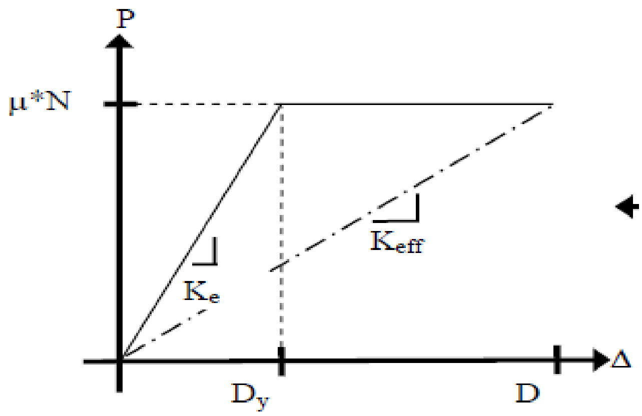

Figure 19: Force-displacement backbone curve (DIS Company)

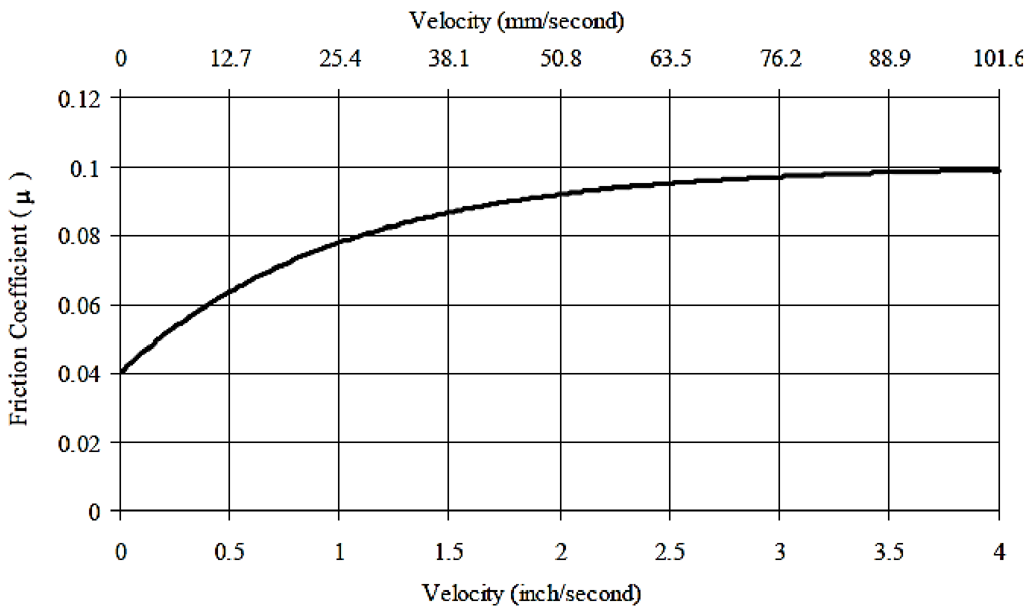

Figure 20: DIS typical friction coefficient vs. velocity curve (DIS Company)

3.5.7 Friction Pendulum Bearing Isolator

The reinforced concrete building is retrofitted using friction pendulum bearing isolator, where it is modeled as spring element and attached to the base of the column after their fixities is released. The stiffness of the base isolator is selected based on trial and error approach, so it yields no collapse prevention hinges after the conduction of the nonlinear history analysis. The properties of the friction pendulum bearing isolator are collected from DIS and presented in Table 3 and designed according to (Naeim, & Kelly 1999) UBC-97. The properties of the sliding bearing isolator are collected from Arathy et al. (Arathy and Manju, 2016).

Table 3: Properties of the selected Friction pendulum bearing isolator.

Properties	**Explanation**	**Magnitude**	**Unit**
K_e	Post-yield stiffness of bearing	0-100000	MPa
μ_{max}	Max coefficient of friction	0.04	Unitless
μ_{min}	Min coefficient of friction	0.02	Unitless
A	Rate parameter	0.05	Meter
RSF	Radius of the sliding surface	0.97	m/s

3.5.8 Hybrid Isolating System

The reinforced concrete building is retrofitted using a mix of two different isolators in order to investigate the effect of using various system in the same structure. The combination of these system composed of flat sliding discussed in section 3.5.6 and lead rubber bearing discussed in section 3.5.5 isolators with the two configurations, the first one consists of flat sliding bearing for the external columns and lead rubber bearing for the internal ones and the second one is vice versa.

3.5.9 Plastic Hinges Properties

Plastic hinges are assigned in accordance with ASCE 41-17. The hinges are assigned at left and right ends for each column and beam at relative distance 0 and 1 respectively as described in ETABS manual. The column hinges are yielding under axial stress (P) and bending moment along both major (M3) and minor (M2) axis. On the other hand, beams hinges are yielding under bending moment along the major axis (M3) only, Where the designed reinforcement is used for both columns and beams.

3.6 Building Design Assumption

The building reinforcement is designed in accordance with TS500 under gravity loads only. Where 2 kN/m^2 is applied on the slab to accommodate the live loads (TS498) and the dead load is the self-load of the structural elements in addition to the additional loads due to the presence of finishing and screeds which is taken as 1.5 kN/m^2. The building is modeled, analyzed and designed using ETABS2017. Figure 16 represents the 3D model of the considered structure.

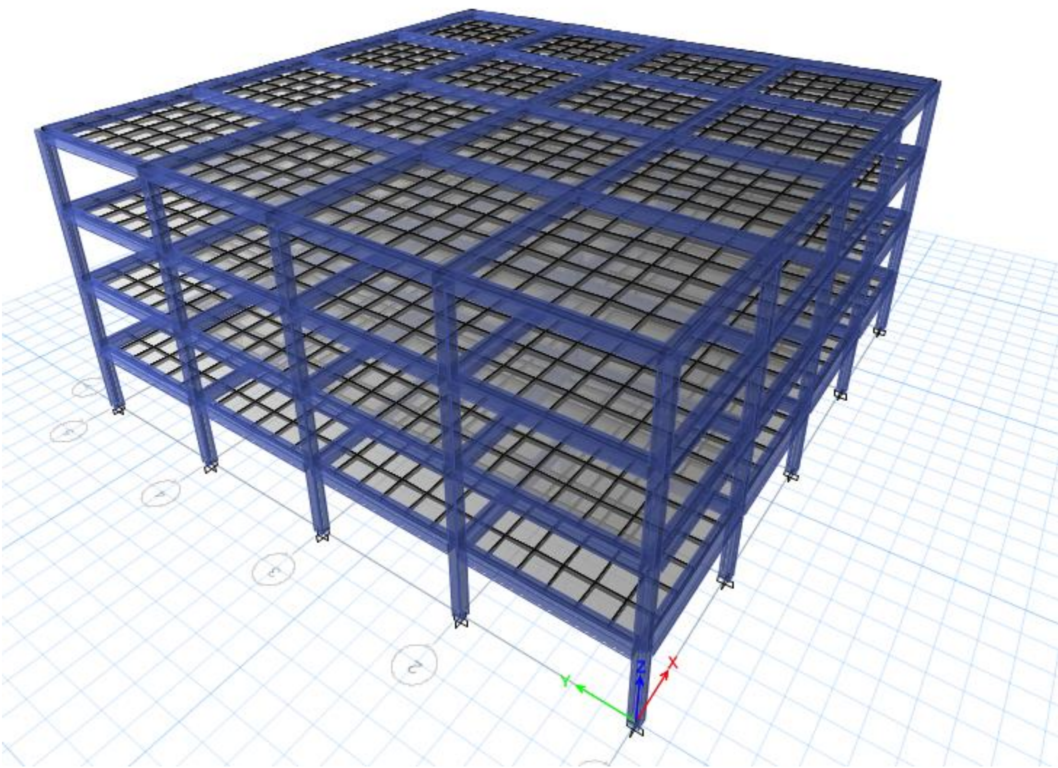

Figure 21: 3D model of the selected case study in ETABS2017.

3.7 Earthquake Load Parameters

The building seismic performance is accessed under equivalent lateral static loads of 10% probability exceedance within 50 years and with respect to nonlinear time history analysis under 2% probability exceedance within 50 years (TBSC2018). The seismic parameters are listed in Table 4 for both 10% and 2% probability of exceedance respectively.

Table 4: The selected location seismic parameters in accordance with TBS2018.

Seismic parameter (TBS2018)	**10% probability**	**2% probability**
Earthquake seismic zone	I	I
Peak ground acceleration	0.548	0.924 g
Site class	ZD	ZD
Importance factor (I)	1	1
Live load contribution factor	0.3	0.3
Short spectral acceleration S_s	1.335	2.359
One second spectral acceleration S_1	0.362	0.639

3.8 Nonlinear Time History Analysis

The behaviour of the structural reinforced concrete building is evaluated by means of nonlinear time history analysis. For this purpose, three different ground motion records are selected that are characterized by different frequencies and magnitudes. The maximum result is used to access the performance as suggested by TBS2018. The ground motion records are collected from PEER center as shown in Table 5. The ground motion records are scaled to match the deign spectra of 2% probability of exceedance within 50% years using time domain scaling method.

Table 5: Selected earthquake records for NRHA.

Year	Earthquake	Earthquake Magnitude (Mw)	PGA (g)	Duration (sec)
1940	Imperial Valley	6.95	0.17814	54
1999	Kocaeli earthquake	7.51	0.2063	28
1999	Düzce earthquake	7.14	0.34613	26

3.9 Modeling in ETABS

the procedure of modelling started by defining the properties of concrete and steel for the fixed base model then using the pre-defined hysteresis model in ETABS for the bearing isolators including LRB, FSB and PFI as a nonlinear link element with the properties shown in Table 1, Table 2, and Table 3 as provided by the manufacturer (DIS) in for modelling a real isolator. Directions U1 (vertical) U2 (horizontal 2) U3 (horizontal 3) are marked and non-linear input data are entered according to each isolator property as shown in appendix IV.

Chapter 4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter includes a summary of the results of the analysis and highlights the major effects of using different base isolators on the performance of RC structures. Furthermore, the behavior of RC buildings retrofitted using LRB isolator with different stiffnesses is going to be presented with emphasizes on energy, acceleration and inter-story drift of the enhanced building.

4.2 Performance of The Fixed Base Model

As mentioned previously the fixed base model was designed to carry gravity loads only, using ETABS as shown in the Figure 22, thereafter, the capacity of the structure were rechecked under the applications of equivalent later load procedure to find the failing elements and to investigate the need for retrofitting. As shown in Figure 23, All the first story columns were collapsed under lateral load which rise the need for retrofitting the structure against earthquake loads.

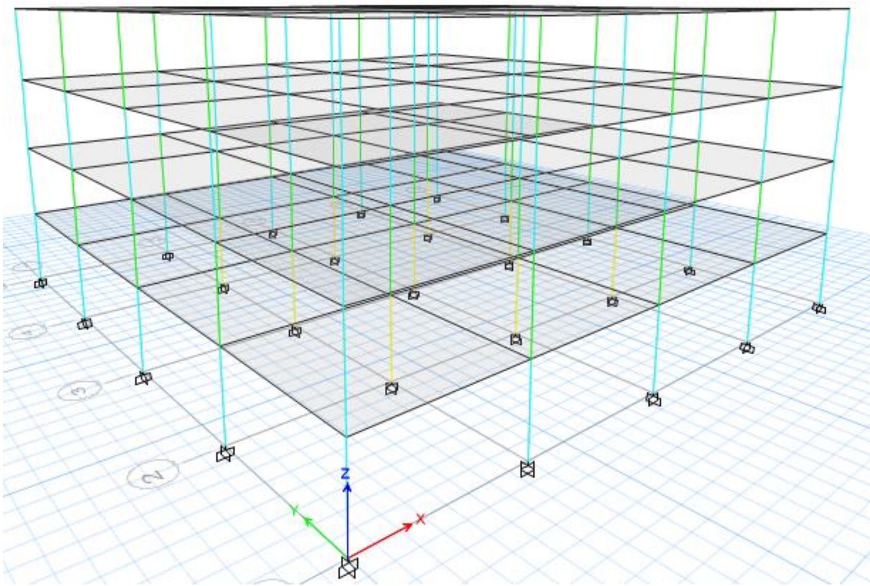

Figure 22: Results of the FB model under gravity load (ETABS)

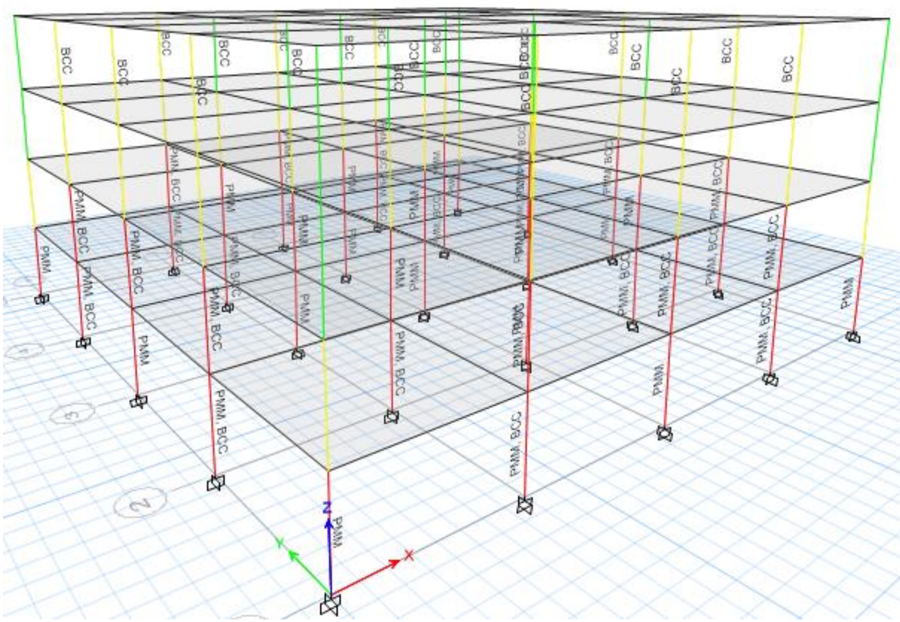

Figure 23: Results of the equivalent lateral load procedure (ETABS)

4.3 Evaluating the Performance of RC Structures Retrofitted Using Lead Rubber Bearing Isolators

This section will discuss the effect of LRB isolators in retrofitting RC structures. As can be seen in Figure 24, when LRB isolators are added to structure its natural period is significantly increased due to the allowing the base column to induce some sort of flexibility to the structure in comparison to the fixed base model. Furthermore, the base shear of the retrofitted structure is decreasing significantly in spite of the isolator stiffness as can be seen in Figure 25 and Figure 26 which is attributed to the deflection in the base of the structure compared to the original structure. This means that using LRB isolators reduces the seismic demand on structures which helps in using smaller lateral load resisting systems.

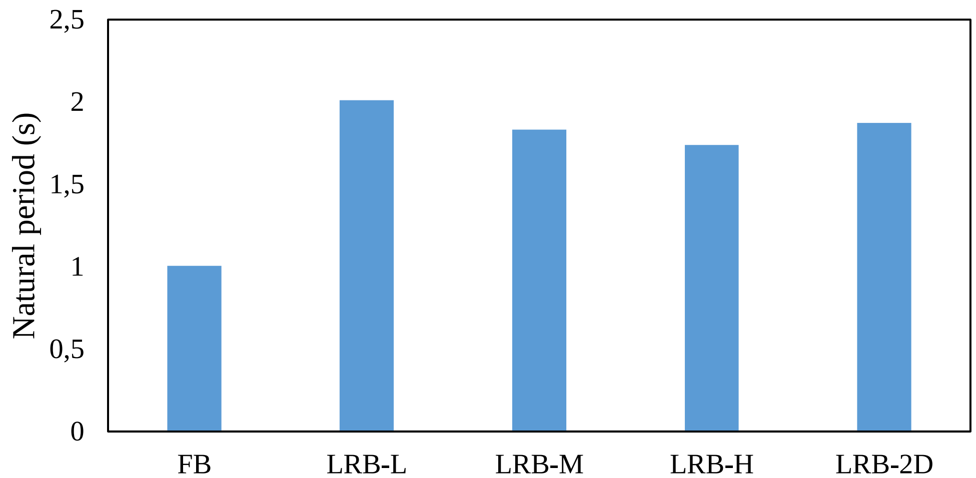

Figure 24: Natural period (s) of LRB isolators models

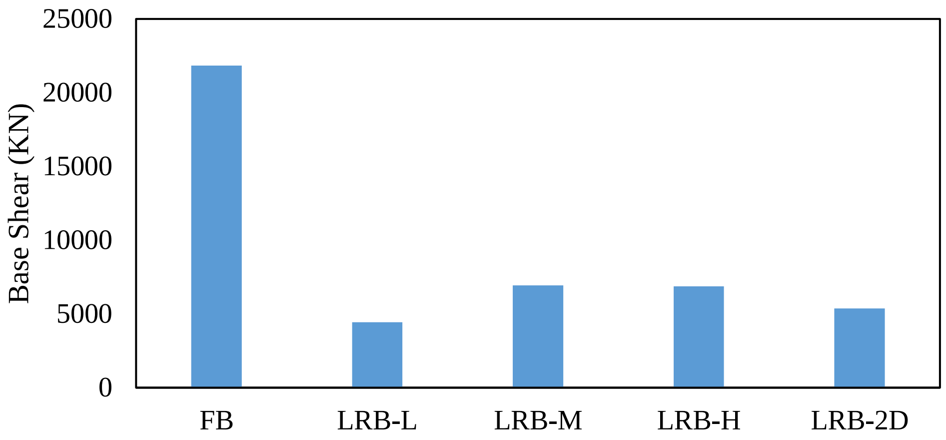

Figure 25: Base shear (KN) in X direction of LRB isolators models

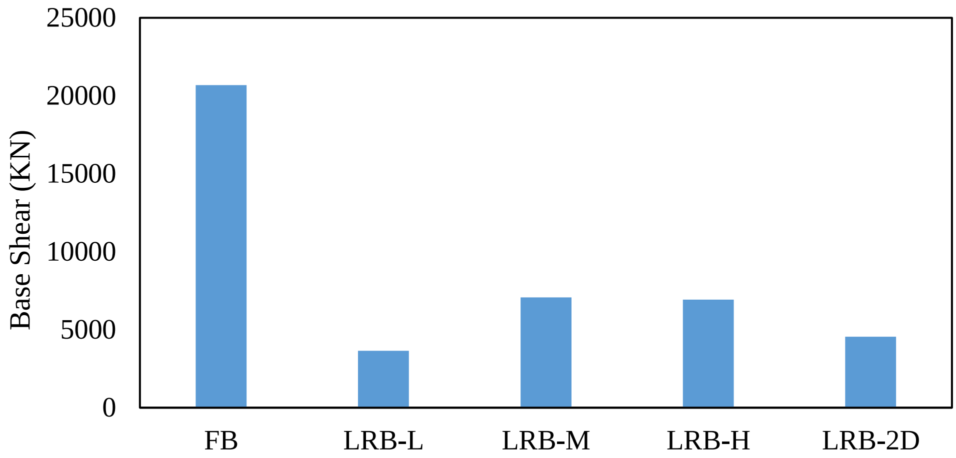

Figure 26: Base shear (KN) in Y direction of LRB isolators models

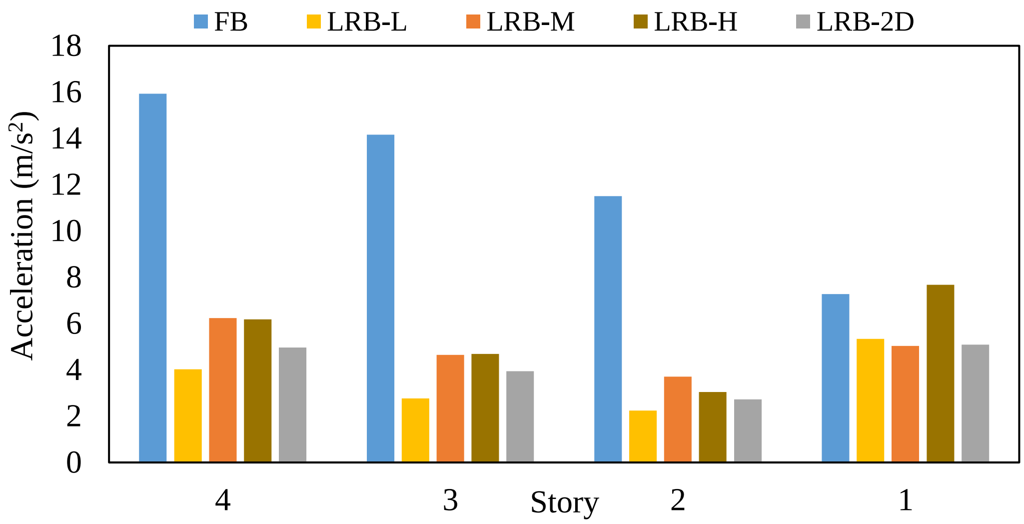

Figure 27: Story acceleration (m/s^2) in X direction of LRB isolators models

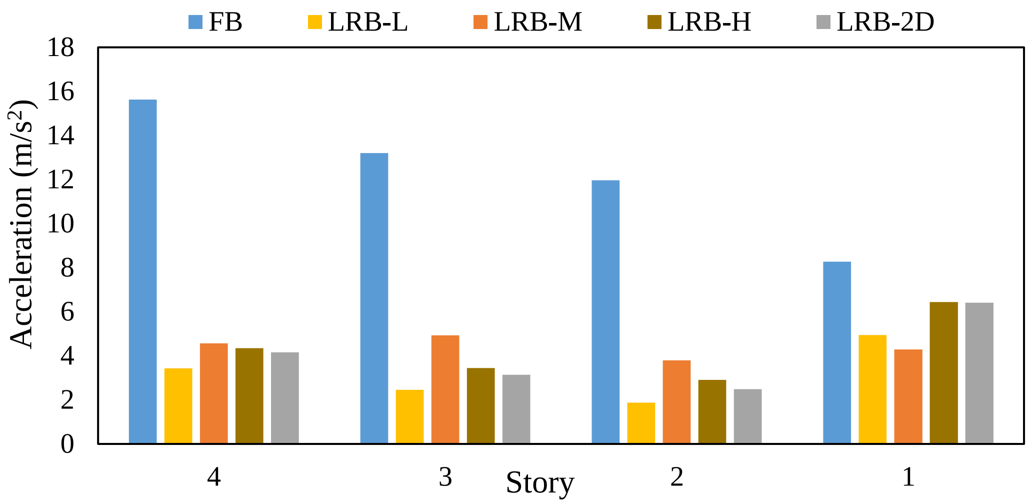

Figure 28: Story acceleration (m/s^2) in Y direction of LRB isolators models

In fact, the story acceleration is another important factor to be controlled in structures. This factor contributes to the damage of nonstrucutral elements such as infill walls. Figure 27 and Figure 28 indicate that while using base isolators the story acceleration in the higher story is decreasing by more than 80% in general, this is attributed to the capability of the retrofitted strucutres to move under the application of ground motion excitations. Furthermore, among all LRB model the LRB-L model showed the most accelptable results in compare to the other models due to the low stiffness of the system which provides heighest capability of deflections.

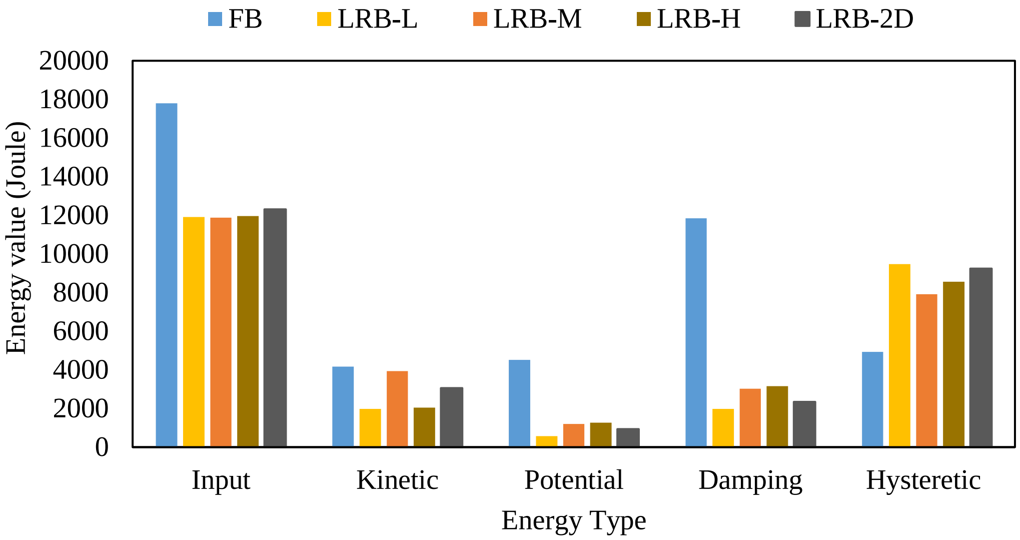

Figure 29: Energy components (Joule) of LRB isolators models

In general, strucutes are damaged during the energy abpsorption process which compose of different components such as kinetic which is the enrgy absorbed during the vibration of the building, potential which is the energy dissipated during the elastic deformation of the strucutral elements, damping is the component related to the energy dissipatted by the viscous damping of the material and structure and the hysteretic which is the energy dissipated through the nonlinear behaivor of the structural members. Figure 29 shows the energy absorption of the LRB models in comparsion to the fixed base model. As can be seen the input energy decreased significantly in the LRB models furthermore, the hysteretic energy were high due to the application of the LRB isolators that dissipated the energy trough a friction process in the isolator itself.

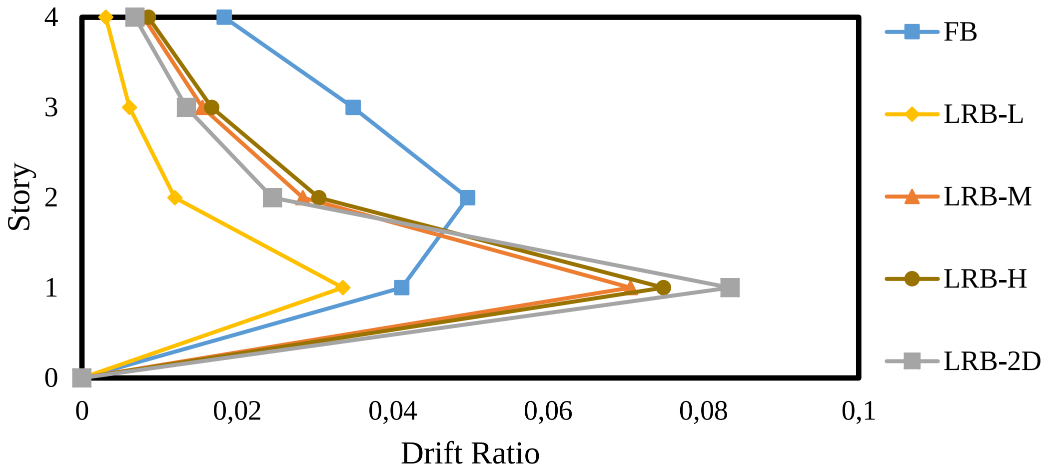

Figure 30: Inter-story drift ratios in X direction of LRB isolators models

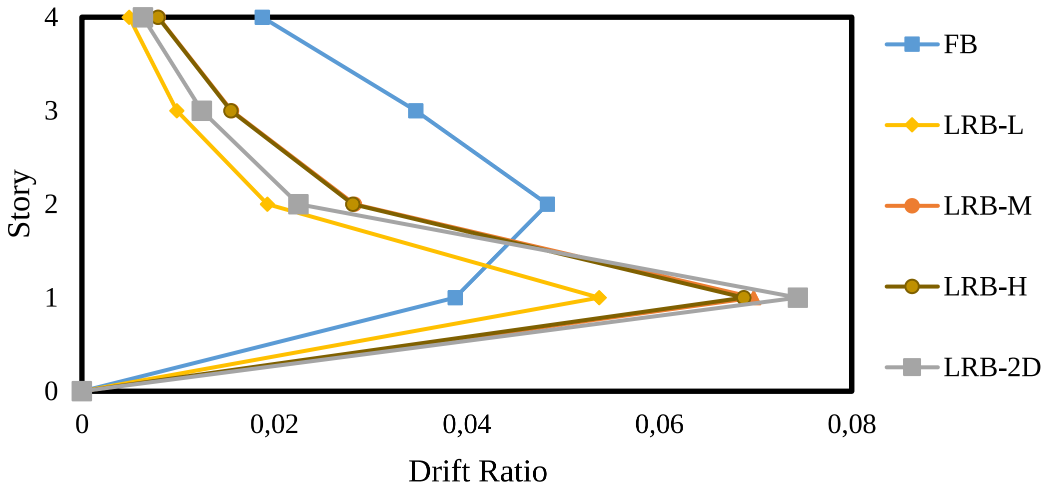

Figure 31: Inter-story drift ratios in X direction of LRB isolators models

Figure 30 and Figure 31 indicate that the inter-story drifts ratio have reduced significantly in the the top stories in the LRB models in comparsion the the FB while the first story showed a higher displacement due to the application of the base isolator. Over all the LRB-L system provided the best solution for the building in terms of lower story drift which means that the strucuter will not face a high displacement and will exhibites a satisfing performance.

Table 6: Performance of LRB isolators

Model	No. of Hinges			Performance Level
	LS	CP	Collapsed	
FB	31	0	4	Collapsed
LRB-L	0	0	0	Life Safety
LRB-M	0	0	2	Collapsed
LRB-H	0	0	2	Collapsed
LRB-2D	0	0	0	Life Safety

In general, this section have provided a detailed invesetigations on the performance of LRB isolators of diffenent sizes and stiffnesse. As can be seen from table 6, the acceptable solution over the propsed ones is LRB-L which showed a good behavior in terms of story drift and number of hinges in addition to overall performance level of the building. And these results that been obtained from adding lead core to to rubber bearing has a similar results form the previous work done by Concellara et al (2013), Li et al (2014) and Concellara et.al (2016)

4.4 Evaluating the Performance of RC Structures Retrofitted Using Different Flat Sliding Bearing Isolators

This section will discuss the effect of (FSB) isolators in retrofitting RC structures. As can be seen in Figure 32, when FSB isolators are added to structure, its natural period is significantly increased which give some flexibility to the structure in comparison to the fixed base model. Furthermore, the base shear of the retrofitted structure is decreasing significantly as can be seen in and Figure 33 and Figure 34 which is attributed to the deflection in the base of the structure compared to the original structure. This means that using FSB isolators reduces the seismic demand on structures which helps in using smaller lateral load resisting systems.

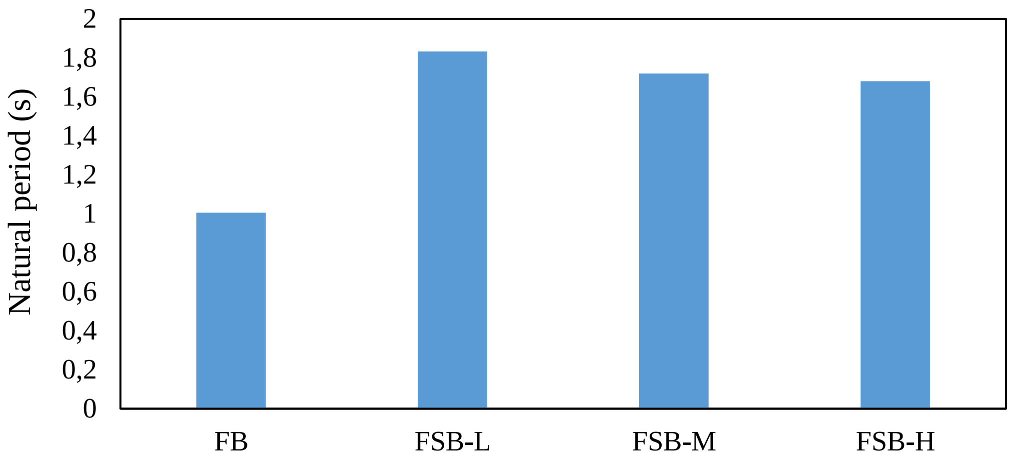

Figure 32: Natural period (s) of FSB isolators models

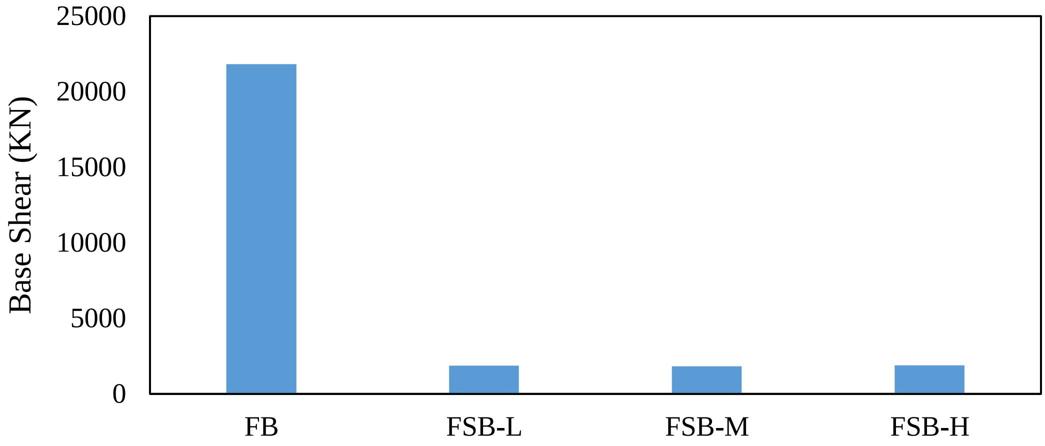

Figure 33: Base shear (KN) in X direction of FSB isolators models

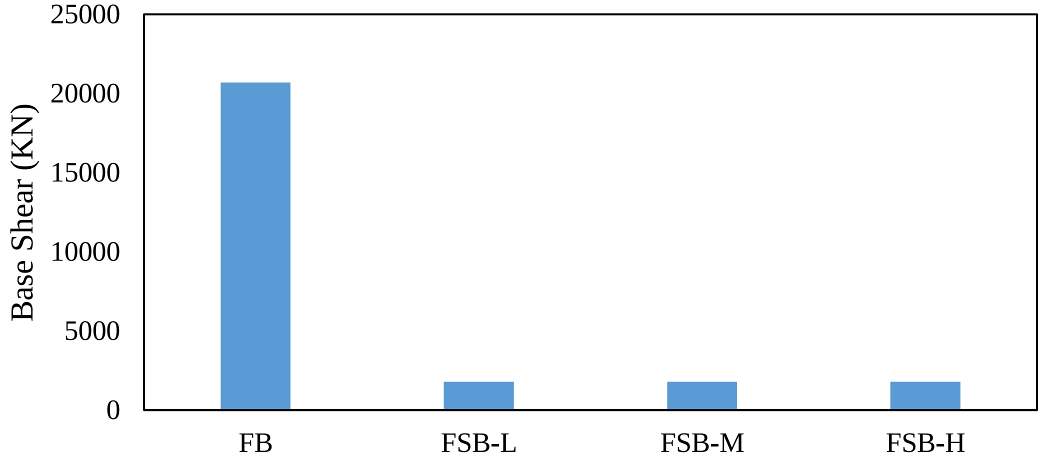

Figure 34: Base shear (KN) in Y direction of FSB isolators models

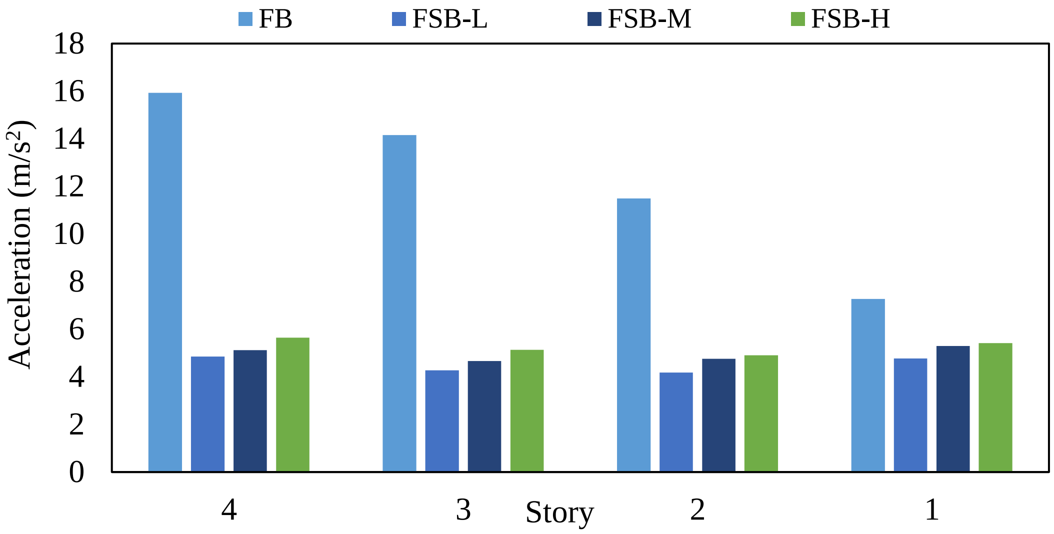

Figure 35: Story acceleration (m/s^2) in X direction of FSB isolators models

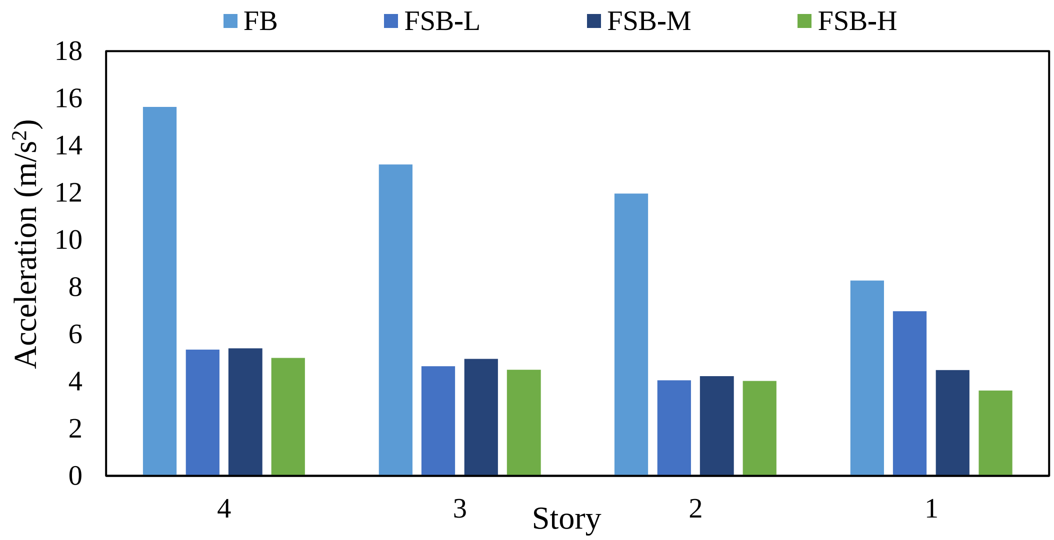

Figure 36: Story acceleration (m/s^2) in Y direction of FSB isolators models

Figure 35 and Figure 36 indicatese that while using base isolators the story acceleration in the higher story is decreasing by more than 60% in general, this is attributed to the capability of the retroifttied strucutres to move under the application of ground motions excitations. Furthermore, among all FSB model the FSB-L model showed the most accelptable results in compare to the other models due to the low stiffness of the system which provides heighest capability of deflections.

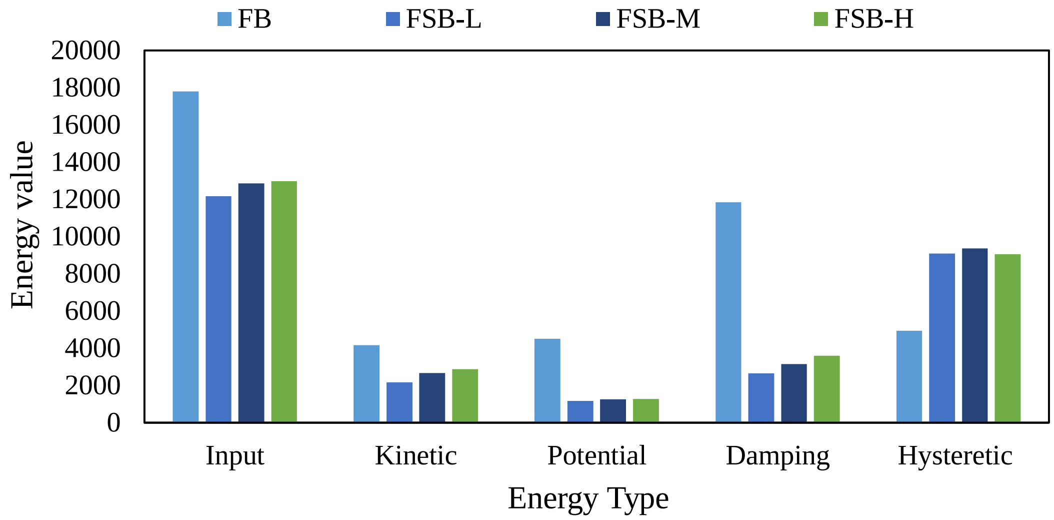

Figure 37: Energy components (Joule) of FSB isolators models

As mentioned previously, strucutes are damaged during the energy abpsorption process which compose of different components such as kinetic, potential, and hysteretic. Figure 37 shows the energy absorption of the FSB models in comparsion to the fixed base model. As can be seen there the input energy decreased significantly in the FSB models. Furthermore, the hysteretic energy was high due to the application of the FSB isolators that dissipated the energy trough a friction process in the isolator itself.

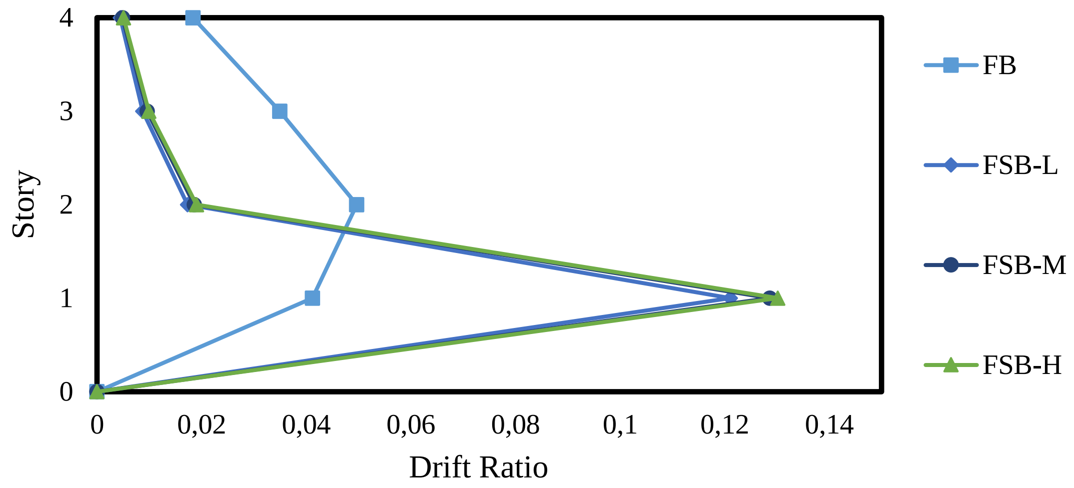

Figure 38: Inter-story drift ratios in X direction of FSB isolators models

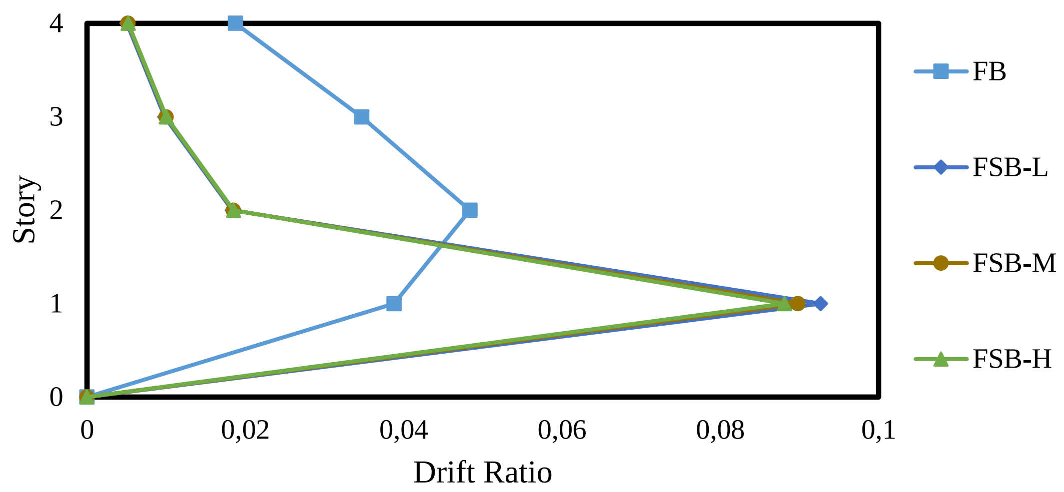

Figure 39: Inter-story drift ratios in Y direction of FSB isolators models

Figure 38 and Figure 39 indicate that the interstory drifts ratio have reduced significantly in the the top stories in the FSB models in comparsion the the FB while the first story showed a higher disiplacement due to the application of the FSB isolator. In fact, all models have provided a very similar behavior which means that similar capability of deforming is expecting regardless of the stiffness of the FSB isolator.

Table 7: Performance of FSB isolators

Model	No. of Hinges			Performance Level
	LS	CP	Collapsed	
FB	31	0	4	Collapsed
FSB-L	9	0	4	Collapsed
FSB-M	7	0	2	Collapsed
FSB-H	8	0	1	Collapsed

In general, this section have provided a detailed invesetigations on the performance of FSB isolators of diffenent sizes and stiffnesses. As can be seen from Table 7 the FSB isolator did not provide an acceptable solution for the FB problem although they enhanced the behavior significatly as we observed a similar enhancing bevaviour from Shenton et al (1993), (Warn and Ryan, 2012) and Li et al (2014). Among our propsed sliding isolators the FSB-H showed the best behavior in terms of number of hinges.

4.5 Evaluating the Performance of RC Structures Retrofitted Using Hybrid Isolator System

This section will discuss the effect of HI system in retrofitting RC structures. As can be seen in Figure 40, when HI systems are added to structure its natural period has the same behavior as LRB and FSB systems in comparison with the FB model. And the same applies on the base shear, accelerations, energy, and story drift behavior as can be seen in Figure 41 and Figure 42.

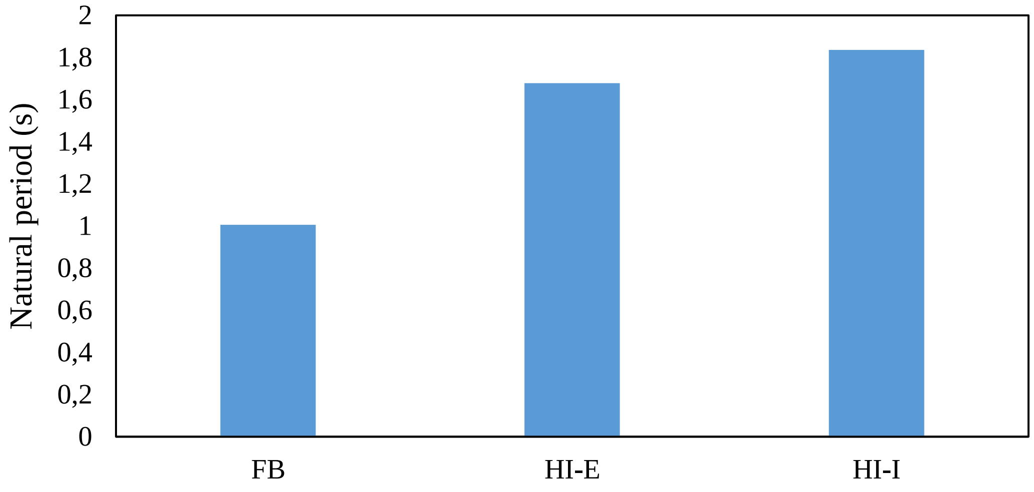

Figure 40: Natural period (s) of HI system models

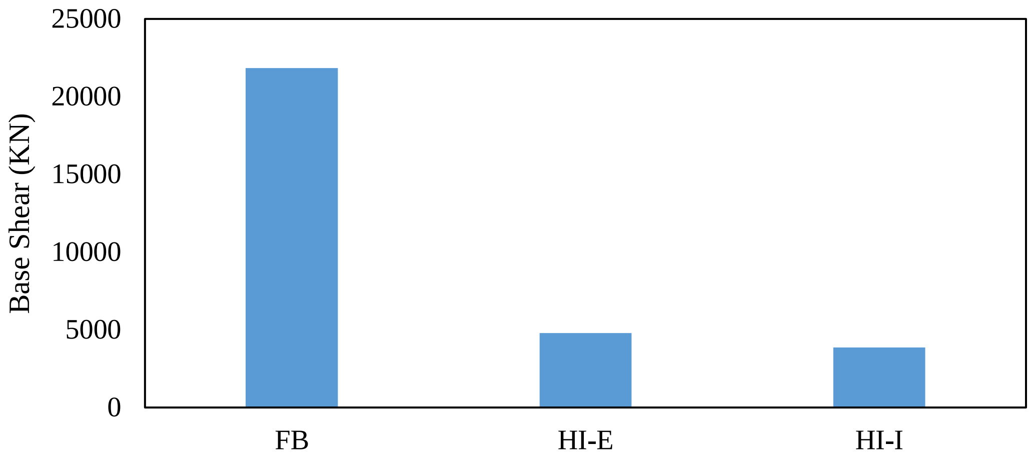

Figure 41: Base shear (KN) in X direction of HI system models

This means that using HI systems reduces the seismic demand on structures which helps in using smaller lateral load resisting systems.

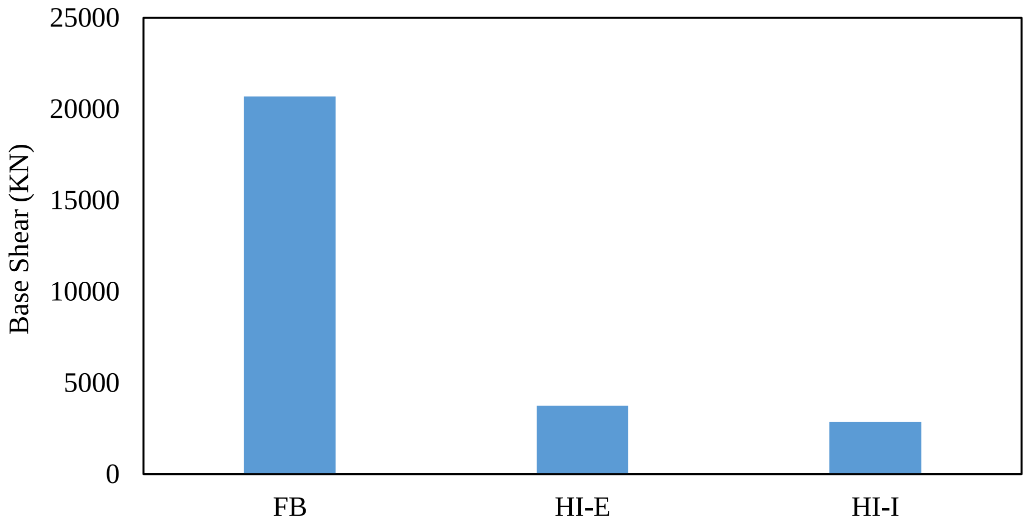

Figure 42: Base shear (KN) in Y direction of HI system models

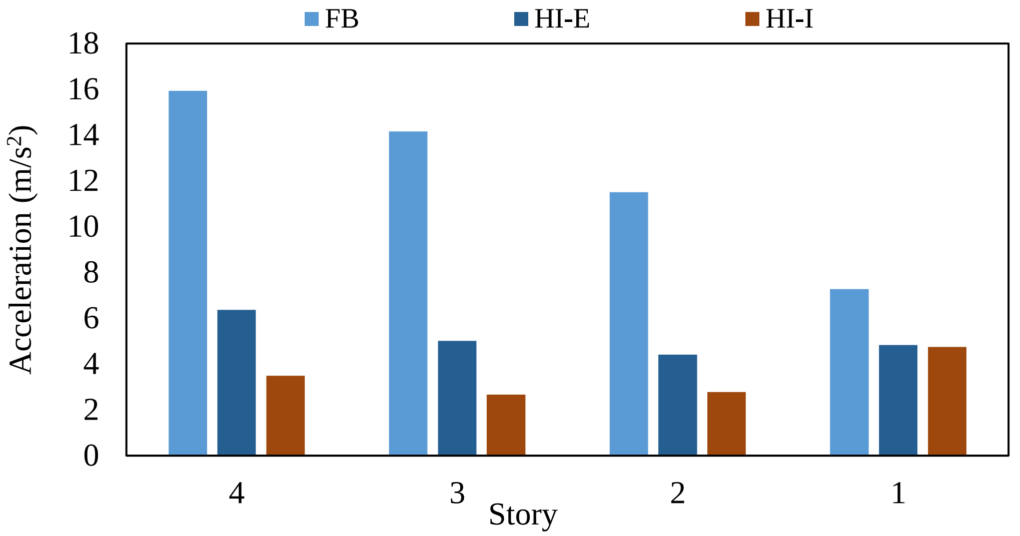

Figure 43: Story acceleration (m/s^2) in X direction of HI system models

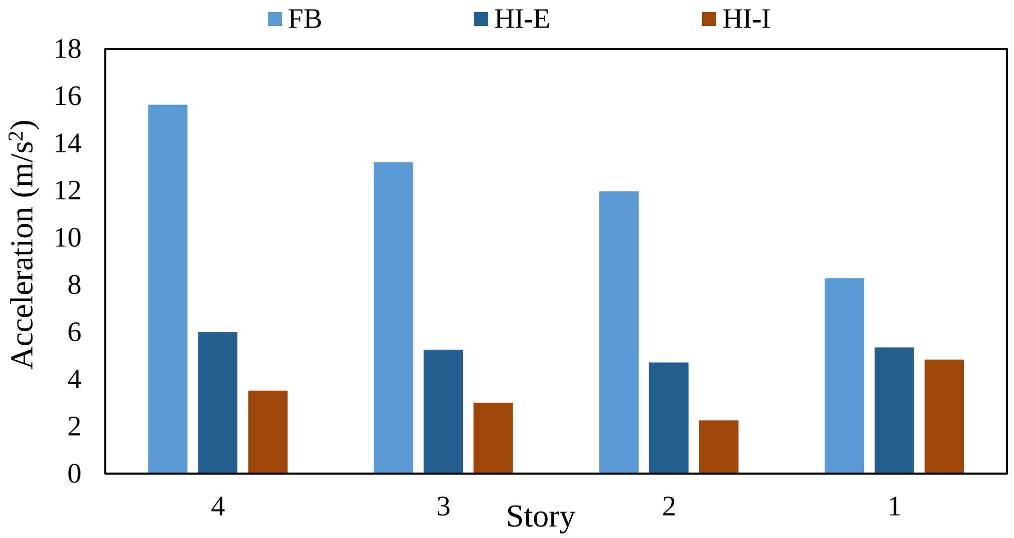

Figure 44: Story acceleration (m/s^2) in Y direction of HI system models

Figure 43 and Figure 44 pointed that while using HI system the higher story acceleration is decreasing by more than 60% in the case of HI-E while it scored over 75% in the case of HI-I. Furthermore, among all HI model the HI-I model showed the most acceptable results in compare to the other models.

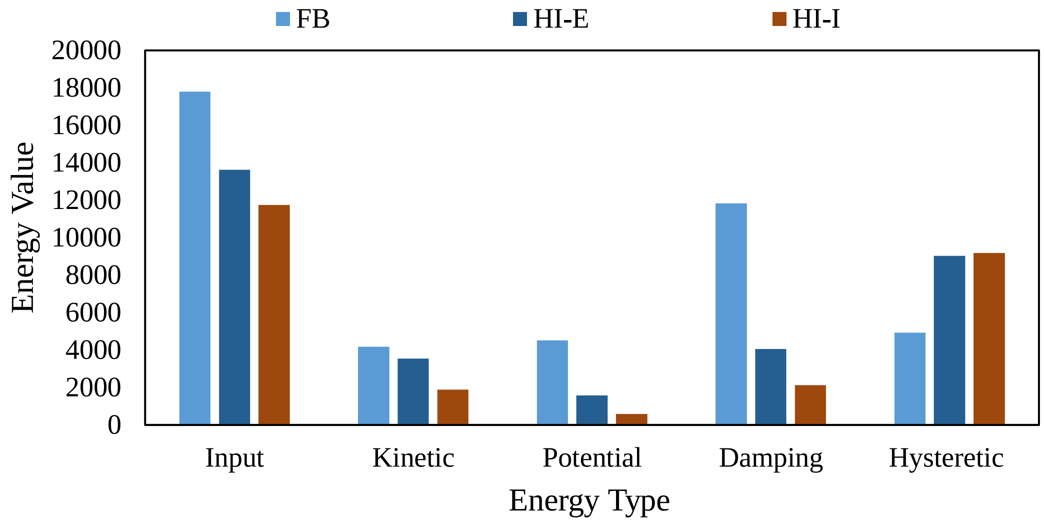

Figure 45: Energy components (Joule) of HI system models

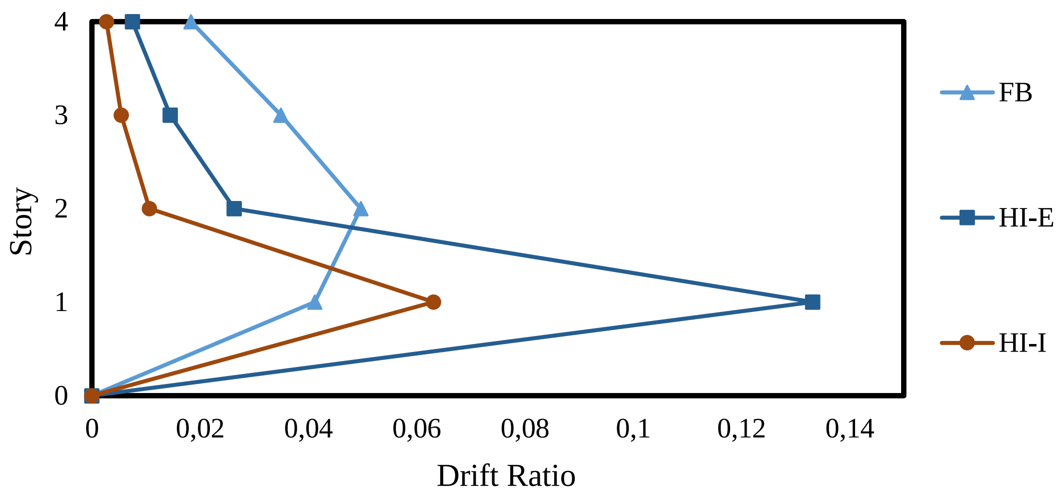

Figure 46: Inter-story drift ratios in X direction of HI system models

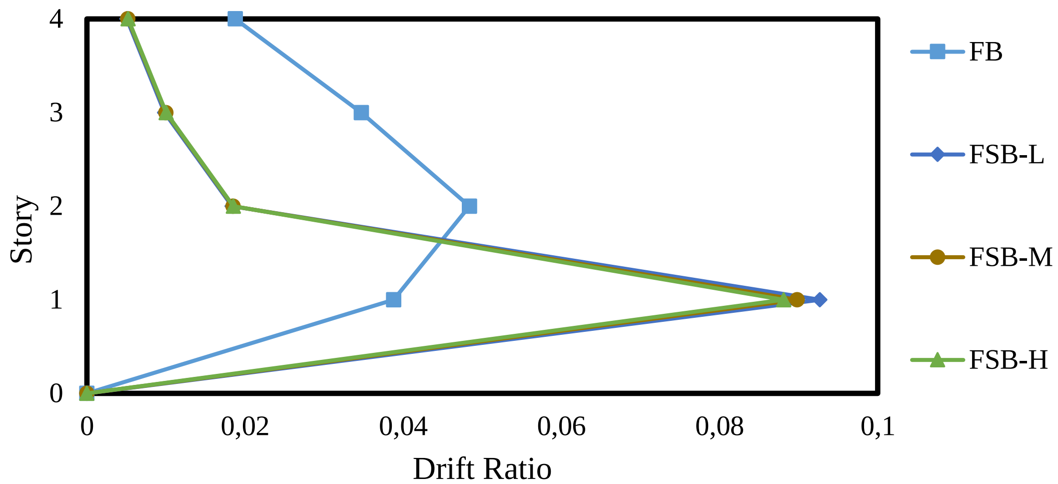

Figure 47: Inter-story drift ratios in Y direction of HI system models

Figure 46 and Figure 47 pointed that the interstory drifts ratio has reduced significantly in the the top stories in the HI models in comparsion the the FB while the first story showed a higher disiplacement due to the application of the base isolator. In fact, both HI models have provided a very similar behavior which means that similar capability of deforming is expecting regardless the stiffness of the arrangment of the isolators.

Table 8: Performance of HI system

Model	No. of Hinges			Performance Level
	LS	CP	Collapsed	
FB	31	0	4	Collapsed
HI-E	9	0	2	Collapsed
HI-I	2	0	0	Life Safety

In general, this section have provided a detailed invesetigations on the performance of HI system with different arrangements of isolators. As can be seen from Table 8 the

HI-I isolator provided an acceptable solution for the FB problem by significatly inhancing the behavior of the original structure in terms of number of hinges.where a similar results has been observed form Concellara et al (2013) and (Markou et al. 2018). when they used a hybrid base isolation system consist of rubber bearing and sliding bearing and in our case we add a lead core to the rubber (lead rubber bearing) in combination with sliding bearing and this system gives similar result regarding the base shear and inter-story drift and disspate more energy due to the lead core.

4.6 Evaluating the Performance of RC Structures Retrofitted Using Various Types of Isolators

This section will compare the effect of the isolators that have been discussed in the previous sections in retrofitting RC structures. As can be seen in Figure 48, Figure 48 when the isolation systems are added to structure the natural period is increased in all systems and gave some flexibility to the structure in comparison to the fixed base model. Furthermore, the base shear decreasing significantly regarding the isolator stiffness as can be seen in Figure 49 and Figure 50 and these base shear results were acceptable and similiar according to the SEAOC recomendatons that had been tested by Shenton et al (1993). This means that using any base isolation system will reduces the seismic demand on structures which helps in using smaller lateral load resisting systems.

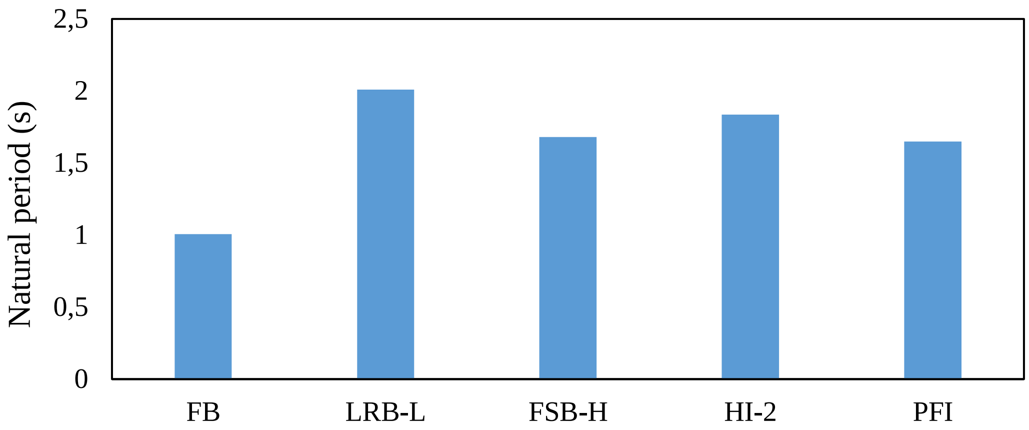

Figure 48: Natural period (s) of various types of isolators models

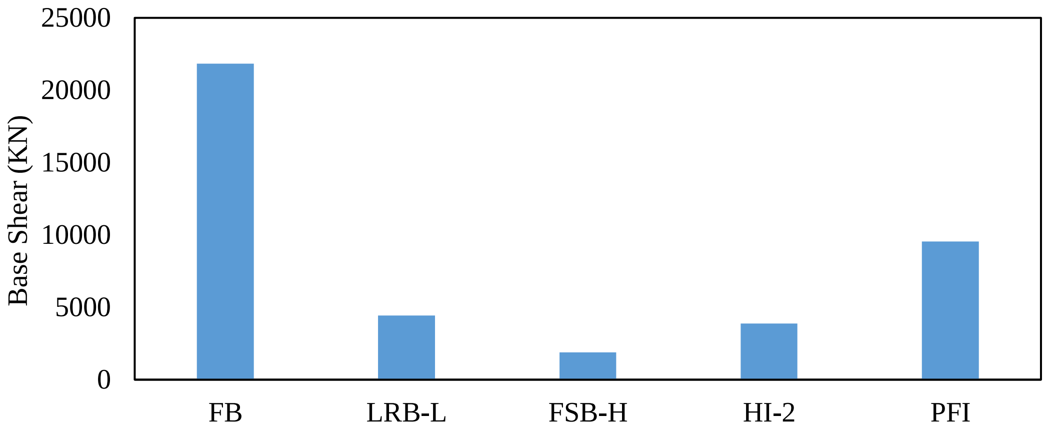

Figure 49: Base shear (KN) in X direction of various types of isolators models

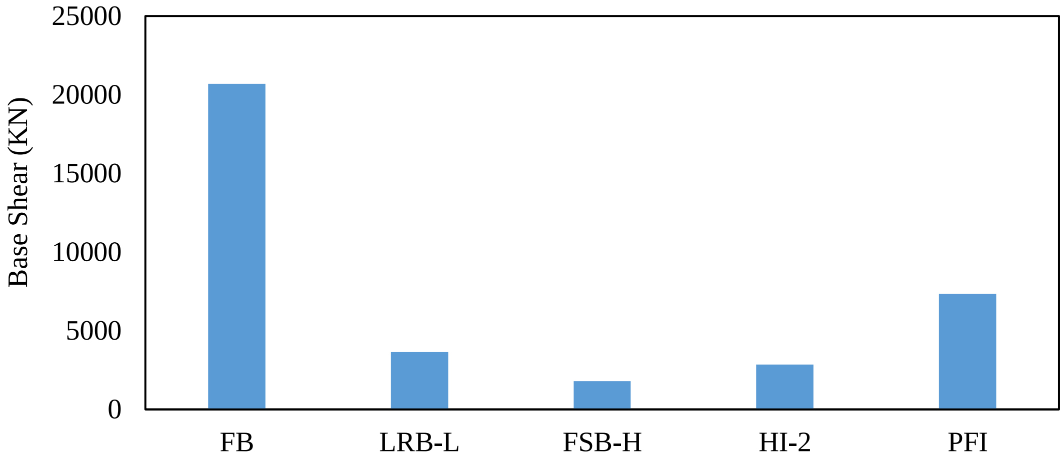

Figure 50: Base shear (KN) in Y direction of various types of isolators models

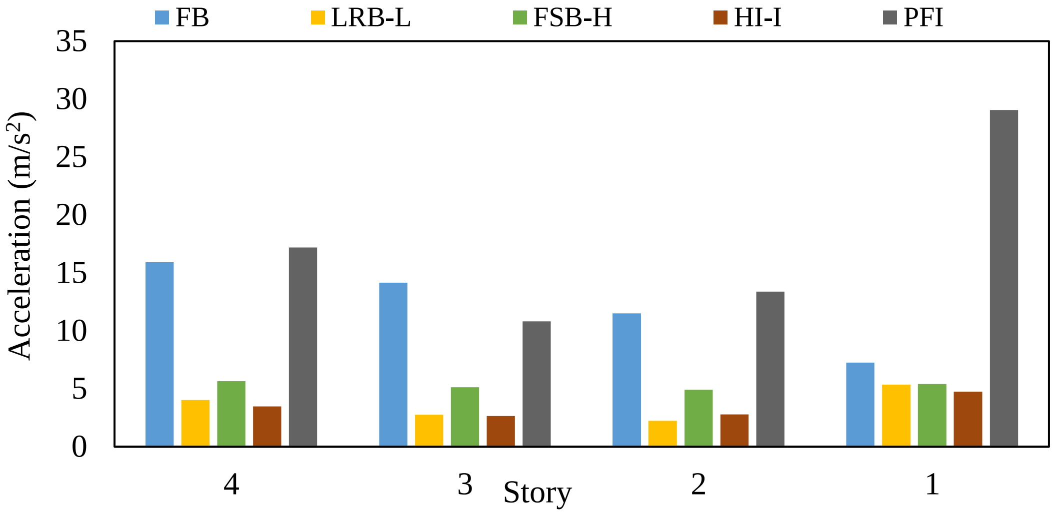

Figure 51: Story acceleration (m/s^2) in X direction of various types of isolators models

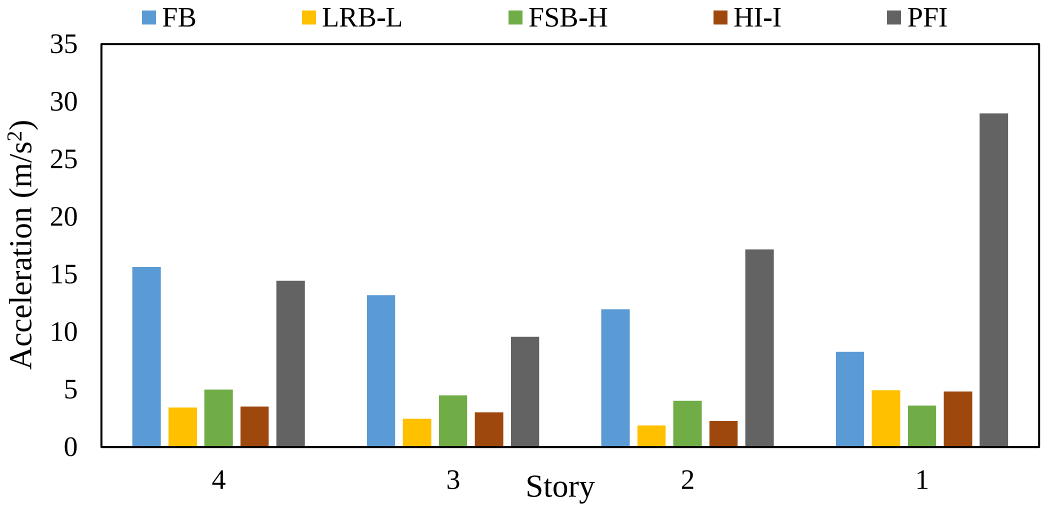

Figure 52: Story acceleration (m/s^2) in Y direction of various types of isolators models

Figure 51 and Figure 52 show that in all base isolatotion systems the higher story accelerations is decreasing by more than 65%, among all base isolation models the PFI model showed the worst results where acceleration has been reduced by 8%. While LRB-L provided the best one.

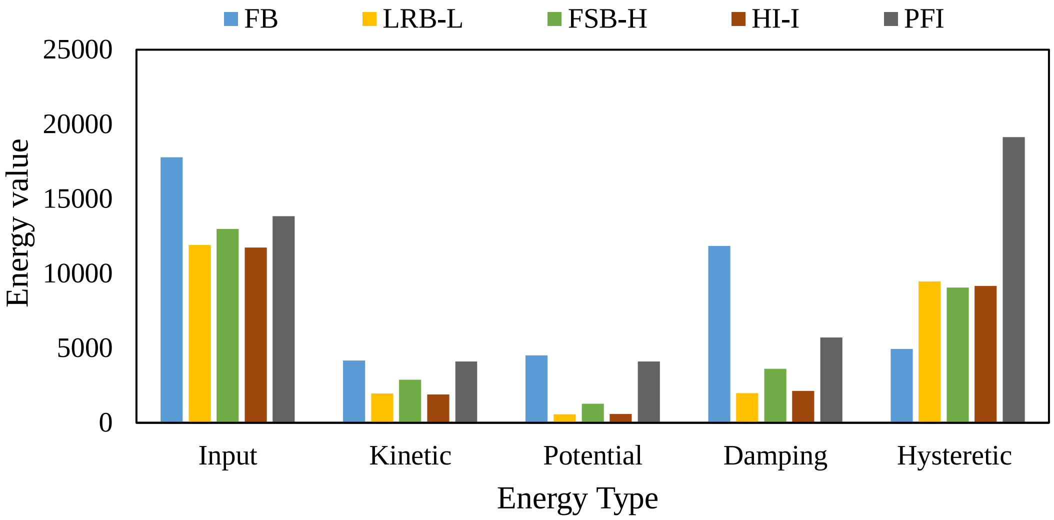

Figure 53: Energy components (Joule) of various types of isolators models

Figure 53 shows the energy absorption of the base isolation models in comparsion to the fixed base model. As can be seen there, the input energy decreased significantly for all isolating models, Furthermore, the hysteretic energy were generally high due to the application of the isolating system that dissipated the energy trough a friction process in the isolator itself.

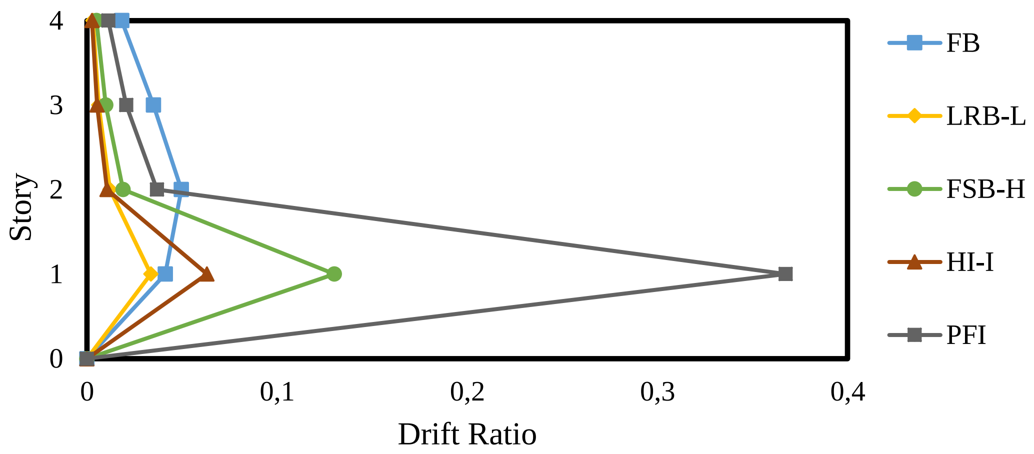

Figure 54: Inter-story drift ratios in X direction of various types of isolators models

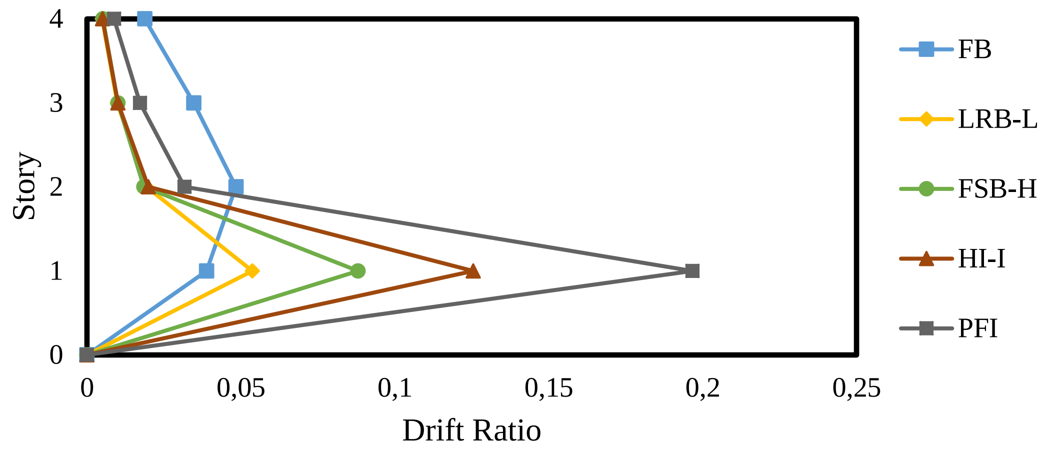

Figure 55: Inter-story drift ratios in Y direction of various types of isolators models

Figure 54 and Figure 55 show interstory drifts ratio have reduced significantly in the the top stories in the retrofitting modles in comparsion the the FB while the first story showed a higher disiplacement specillay the PFI modle due to its high sliding capability. In fact, the best drift behavior is found in the case of LRB-L in comparison to all other retrofitting models.

Table 9: Performance of various types of isolators

Model	No. of Hinges			Performance Level
	LS	CP	Collapsed	
FB	31	0	4	Collapsed
LRB-L	0	0	0	Life Safety
FSB-H	8	0	1	Collapsed
HI-I	2	0	0	Life Safety
PFI	20	0	2	Collapsed

In general, this section have provided a detailed invesetigations on the performance of base isolated buiding with different types of isolators. As can be seen from Table 9 LSB-L isolator provided an acceptable solution for the FB problem by significatly enhancing the behavior of the original structure in terms of base shear, acceleration, interstory drift ratio and number of hinges.

Chapter 5

CONCLUSION

5.1 Summary

This study has contributed to the investigation of the application of base isolator. As part of the study different types of base isolators were used to seismically retrofitted RC structure. The following points can be concluded:

- Adding base isolator system to structure increases its natural period significantly by around 30%.
- Base isolators can reduce the seismic demand of structures by means of decreasing its base shear by over 70%.
- In general, for low to midrise buildings conventional LRB isolators are capable of improving their performance significantly against earthquake records.
- Regardless of the isolator type the energy input can be reduced by a minimum amount of 20% and maximum amount of 55% when the control system is implemented to the building.
- Base isolators are capable of decreasing the story accelerations with an average of 65%, which helps in reducing the damage of non-structural elements.
- Finally, base isolator dissipates their energy through hysteretic behavior which means the energy is absorbed through friction process.

5.2 Recommendations

In this study we used mainly lead rubber bearing and two types of sliding bearing which are flat sliding bearing and friction pendulum bearing in addition to a hybrid system mixing a flat sliding and lead rubber bearings. For recommendations about future studies:

- Same study can be suggested to analyze the effect of other types of isolators such as double pendulum and triple pendulum systems.
- Using the hybrid isolation system can open the door for new possibilities of trying to apply more than one type of isolator on structures like applying viscous dampers in combinations with lead rubber bearings.
- The considered model within the studied was regular reinforced concrete structure where irregular structural systems might possess different behavior. Hence, studies that consider the behavior of seismic isolators on structural systems with irregularities along both the plan and elevation of the structure is recommended by the author.
- A study on the cost of base isolation systems will add more value to the conducted research.

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APPENDICES

Appendix A: Ground Motion Records

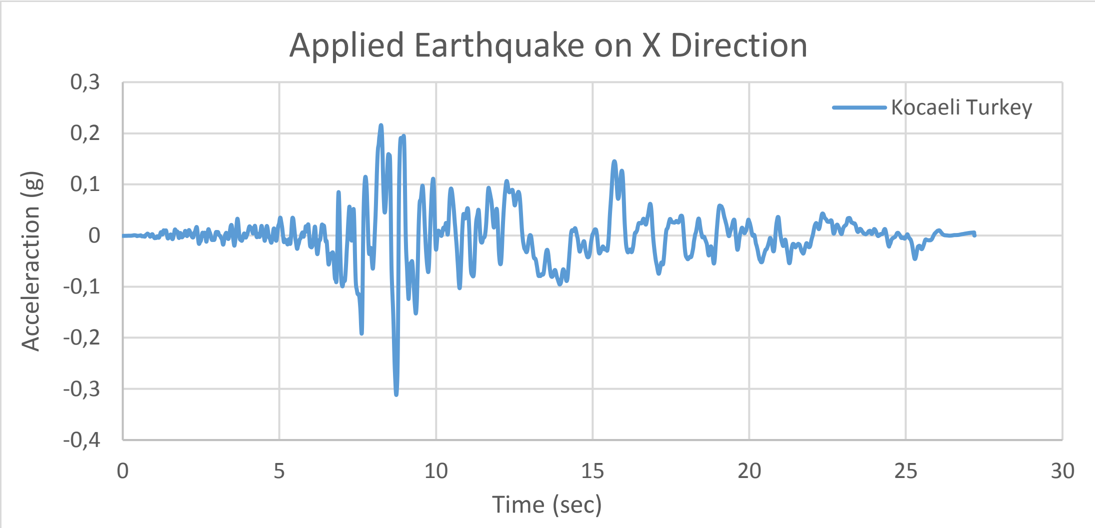

Figure A.1: Koceli earthquake commponent in X direction.

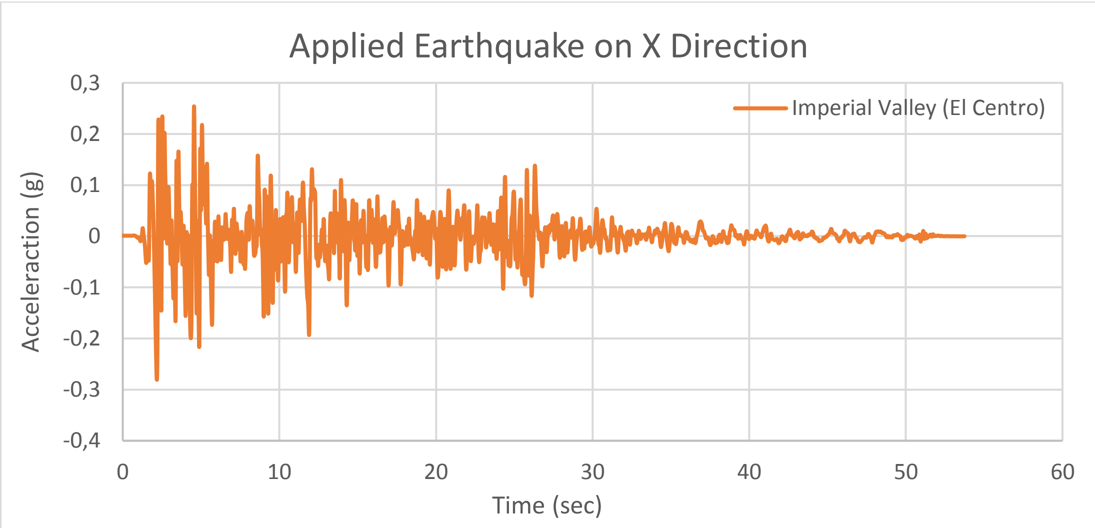

Figure A.2: Imperial Valley earthquake commponent in X direction.

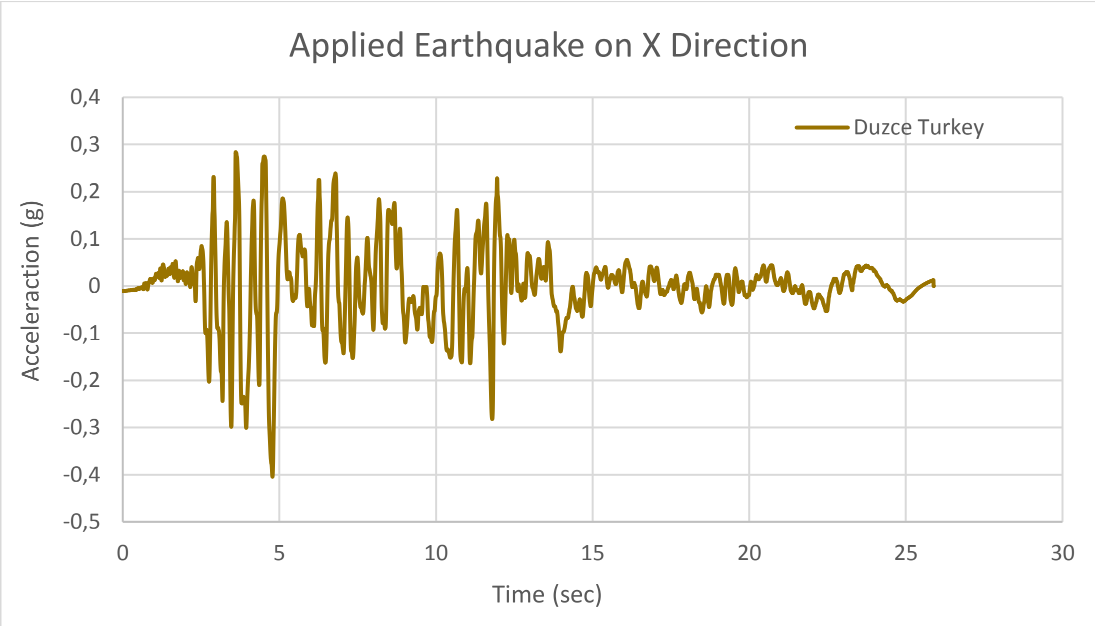

Figure A.3: Duzce earthquake commponent in X direction.

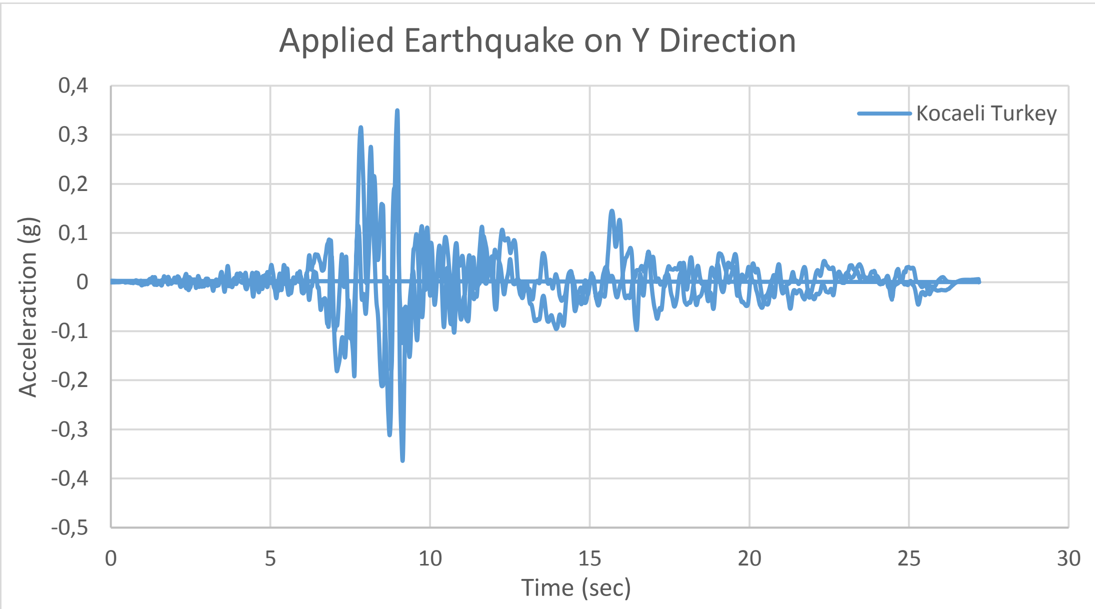

Figure A.4: Koceli earthquake commponent in Y direction

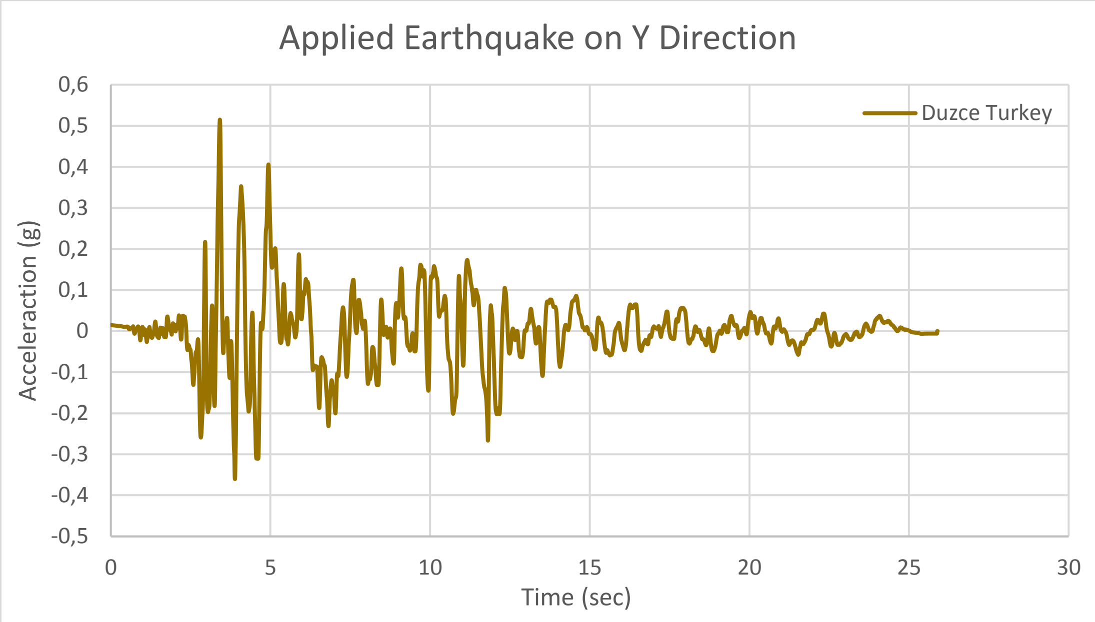

Figure A.5: Duzce earthquake commponent in Y direction

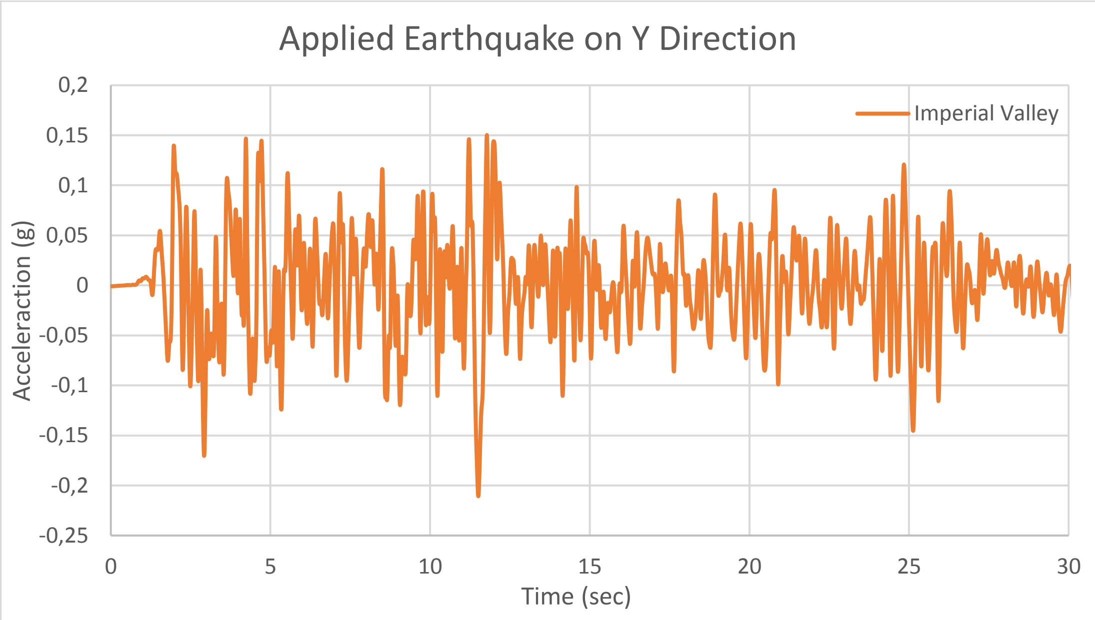

Figure A.6: Imperial Valley earthquake commponent in Y direction

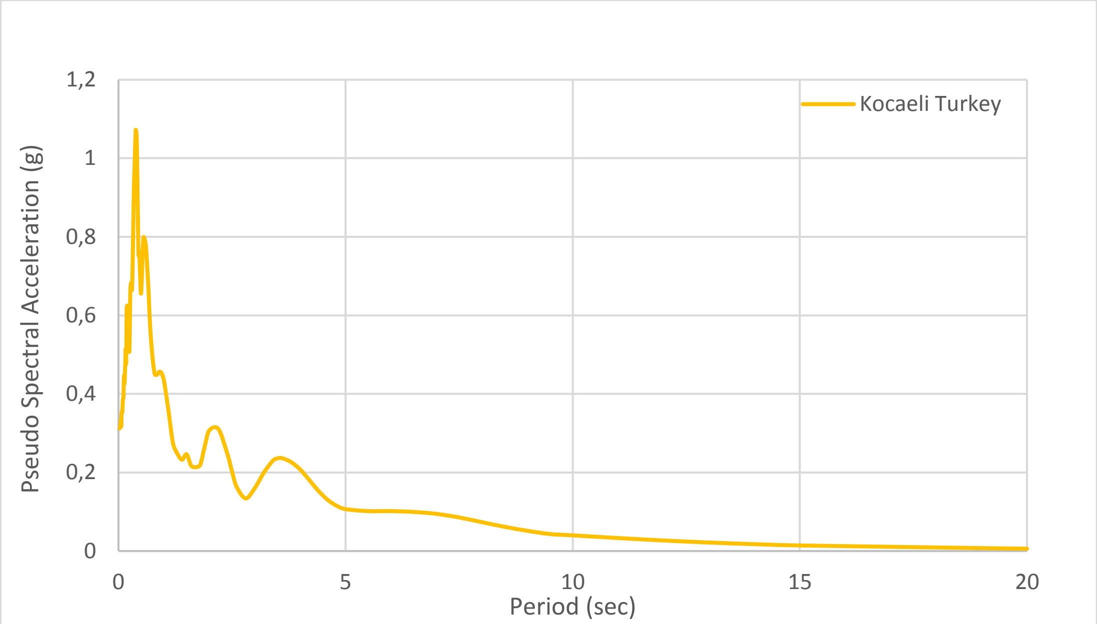

Figure A.7: Horizontal Spectra for Kocaeli in X Direction

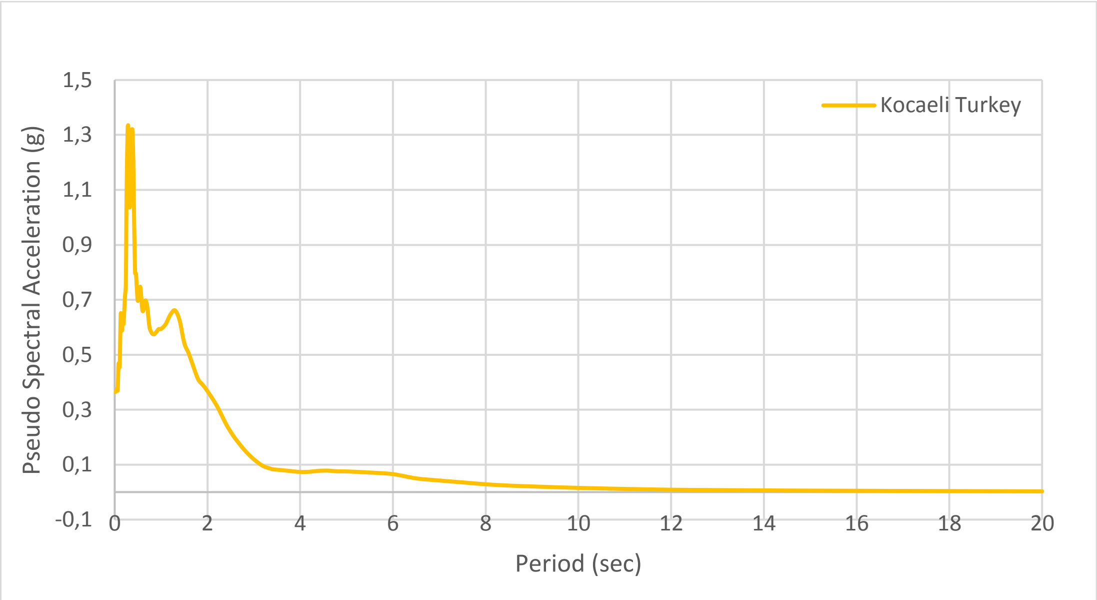

Figure A.8: Horizontal Spectra for Kocaeli in Y Direction

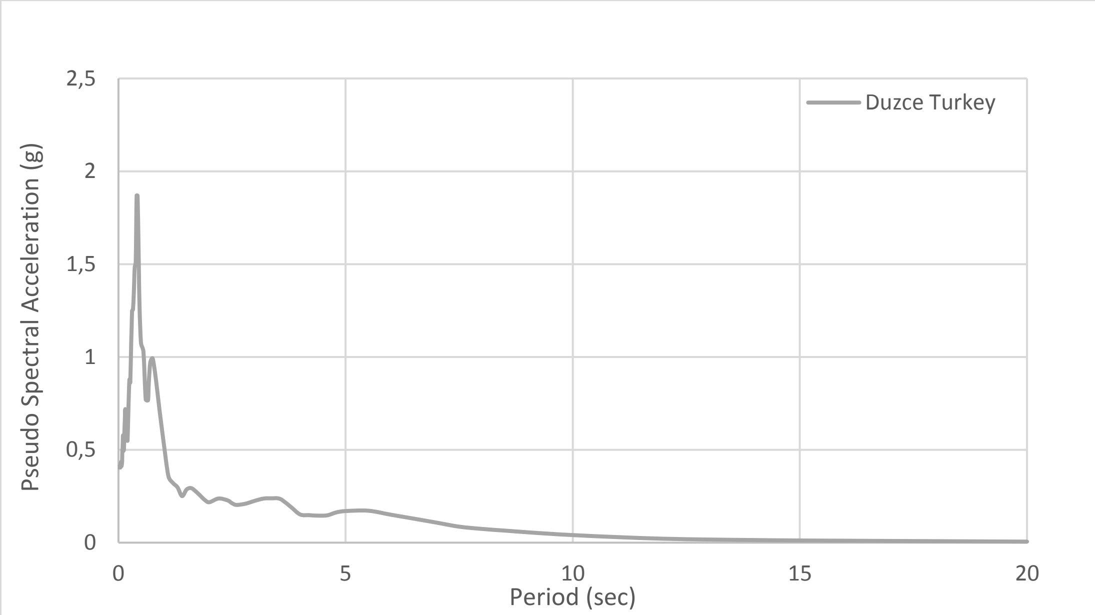

Figure A.9: Horizontal Spectra for Duzce in X Direction

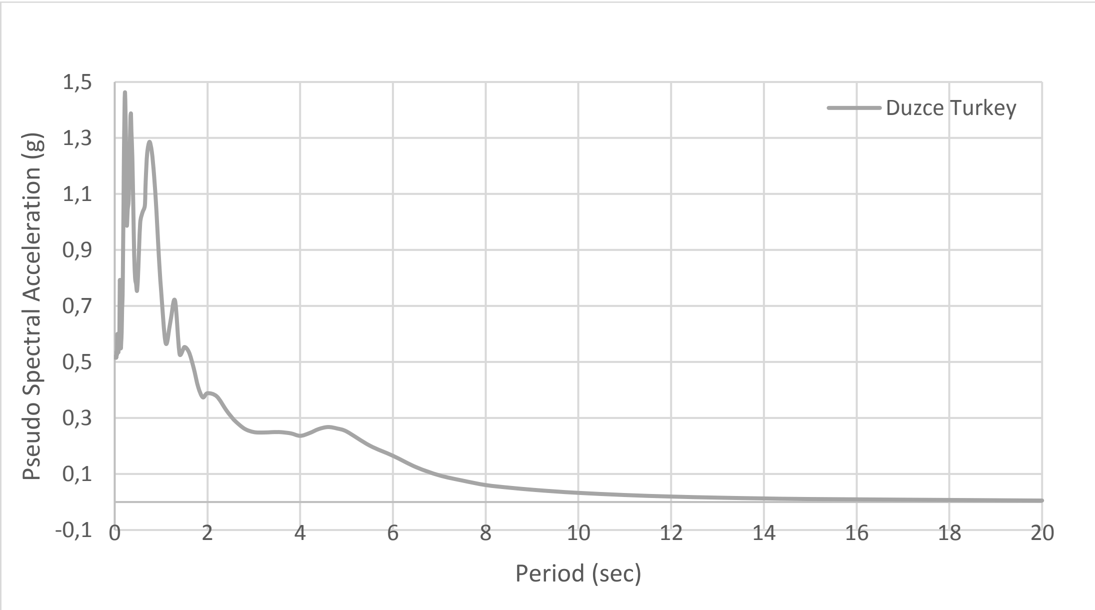

Figure A.10: : Horizontal Spectra for Duzce in Y Direction

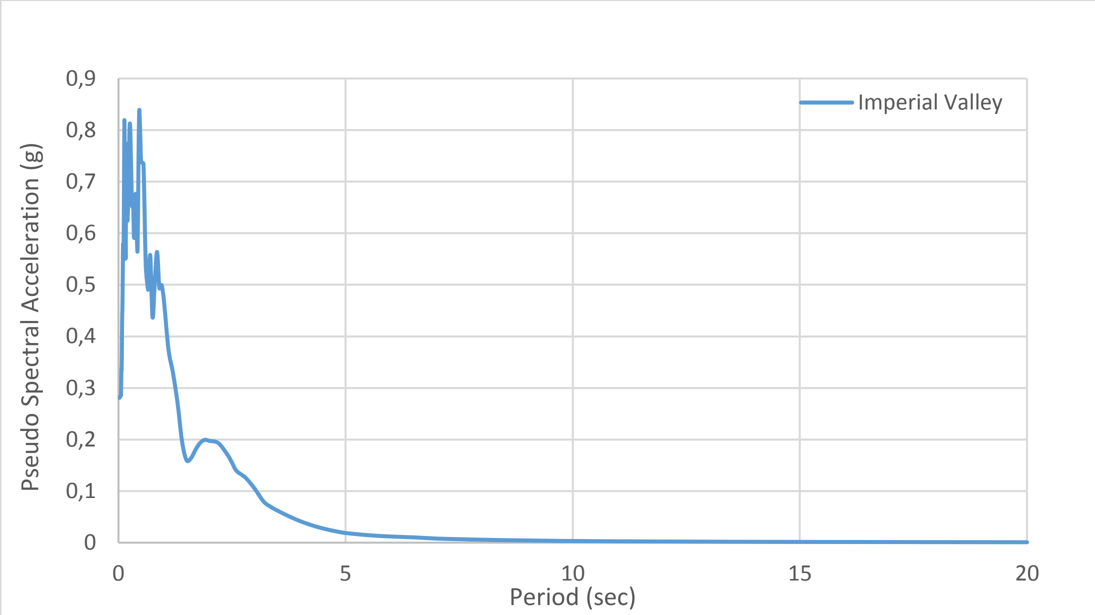

Figure A.11: Horizontal Spectra for Imperial Valley in X direction

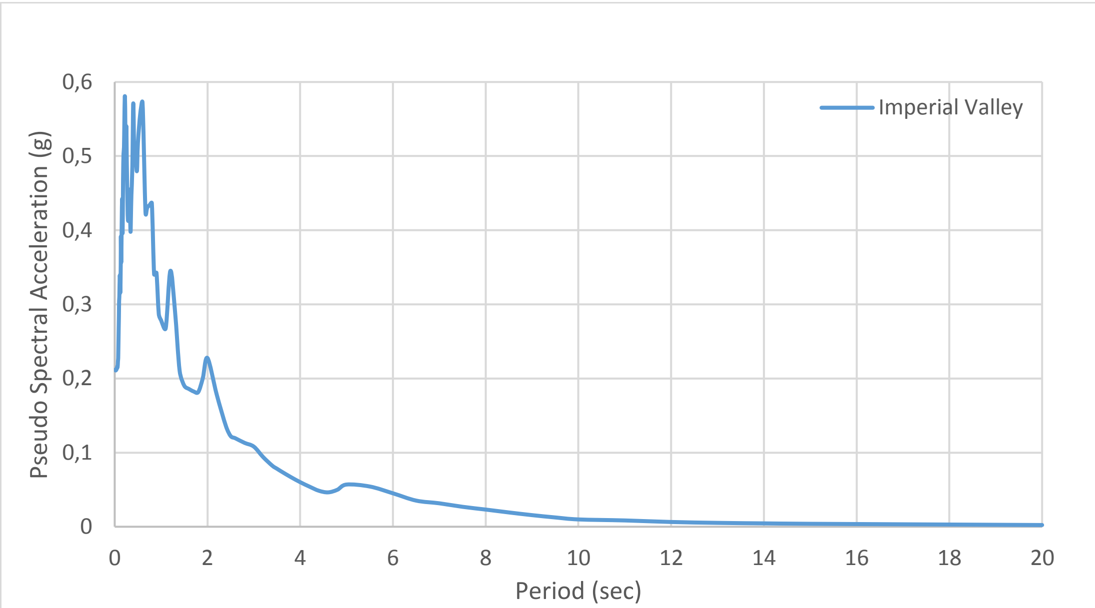

Figure A.12: Horizontal Spectra for Imperial Valley in Y direction

Appendix B: Response Spectrum

10% Response spectrum according to the new earthquake Turkish standard.

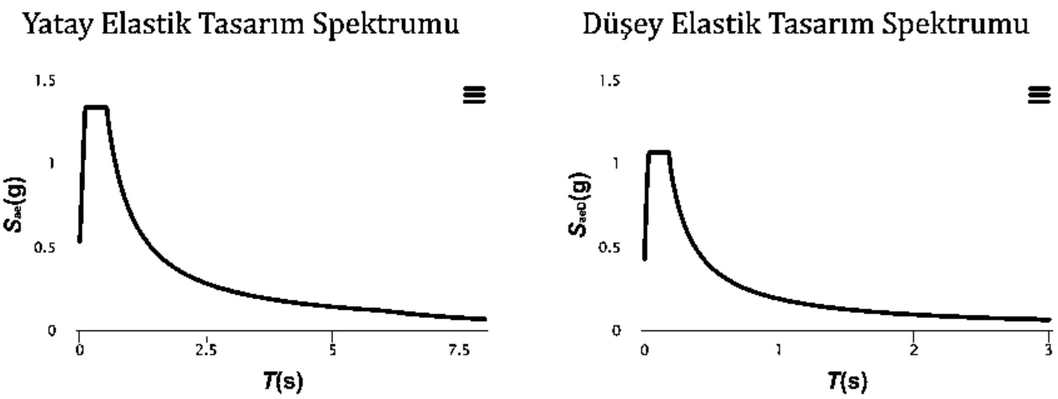

Figure B.1: Horizontal (left) and Vertical (right) elastic design spectrom

2% Response spectrum according to the new earthquake Turkish standard.

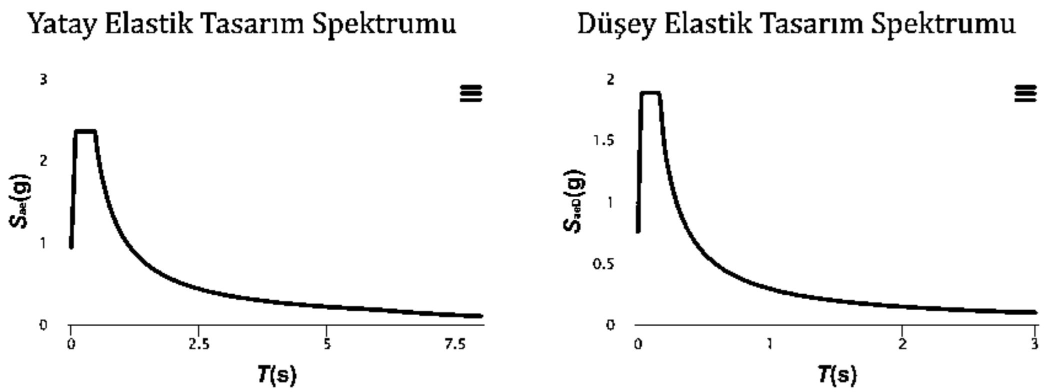

Figure B.2: Horizontal (left) and Vertical (right) elastic design spectrom

Appendix C: Isolator Data

Table C.1: Metric units for isolators properties

DEVICE SIZE				MOUNTING PLATE DIMENSIONS					
Isolator Diameter, D_I (mm)	Isolator Height, H (mm)	Number of Rubber Layers, N	Lead Diameter D_L (mm)	L (mm)	t (mm)	Hole Qty.	Hole Ø (mm)	A (mm)	B (mm)
305	125-280	4-14	0-100	355	25	4	27	50	-
355	150-305	5-16	0-100	405	25	4	27	50	-
405	175-330	6-20	0-125	455	25	4	27	50	-
455	175-355	6-20	0-125	510	25	4	27	50	-
520	205-380	8-24	0-180	570	25	8	27	50	50
570	205-380	8-24	0-180	620	25	8	27	50	50
650	205-380	8-24	0-205	700	32	8	27	50	50
700	205-430	8-30	0-205	750	32	8	33	65	75
750	230-455	8-30	0-230	800	32	8	33	65	75
800	230-510	8-33	0-230	850	32	8	33	65	75
850	230-535	8-35	0-255	900	38	12	33	65	95
900	255-560	9-37	0-255	955	38	12	33	65	95
950	255-585	10-40	0-280	1005	38	12	33	65	95
1000	280-635	11-40	0-280	1055	38	12	40	75	115
1050	305-660	12-45	0-305	1105	44	12	40	75	115
1160	330-760	14-45	0-330	1205	44	12	40	75	115
1260	355-760	16-45	0-355	1335	44	16	40	75	115
1360	405-760	18-45	0-380	1435	51	16	40	75	115
1450	430-760	20-45	0-405	1525	51	20	40	75	115
1550	455-760	22-45	0-405	1625	51	20	40	75	115

Table C.2: Design properties of the isolators

Isolator Diameter, D_I (mm)	DESIGN PROPERTIES Yielded Stiffness, K_d(kN/mm)	Characteristic Strength Q_d(kN)	Compression Stiffness, K_v(kN/mm)	Maximum Displacement, D_{max}(mm)	Axial Load Capacity P_{max}(kN)
305	0.2-0.9	0-65	>50	150	450
355	0.2-1.2	0-65	>100	150	700
405	0.3-1.6	0-110	>100	200	900
455	0.3-2.0	0-110	>100	250	1,150
520	0.4-2.3	0-180	>200	300	1,350
570	0.5-2.8	0-180	>500	360	1,800
650	0.5-3.5	0-220	>700	410	2,700
700	0.5-4.2	0-220	>800	460	3,100
750	0.7-4.7	0-265	>900	460	3,600
800	0.7-5.3	0-265	>1,000	510	4,000
850	0.7-6.1	0-355	>1,200	560	4,900
900	0.7-6.1	0-355	>1,400	560	5,800
950	0.7-6.1	0-490	>1,800	610	6,700
1000	0.8-6.3	0-490	>1,900	660	7,600
1050	0.9-6.3	0-580	>2,100	710	8,500
1160	1.1-6.5	0-665	>2,800	760	13,800
1260	1.2-6.7	0-755	>3,700	810	20,500
1360	1.4-7.0	0-890	>5,100	860	27,600
1450	1.6-7.2	0-1,025	>5,300	910	33,400
1550	1.8-7.4	0-1,025	>6,500	910	40,000

Appendix D: Modeling in ETABS

Rubber isolator bearing

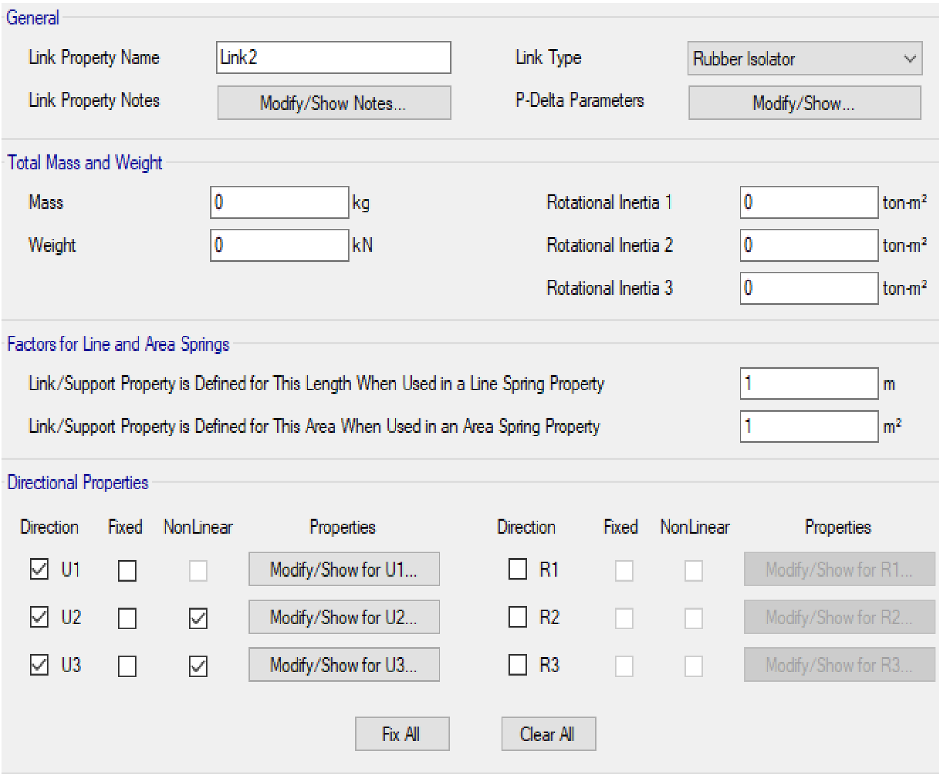

Figure D.1: Defining the isolator link in ETAPS

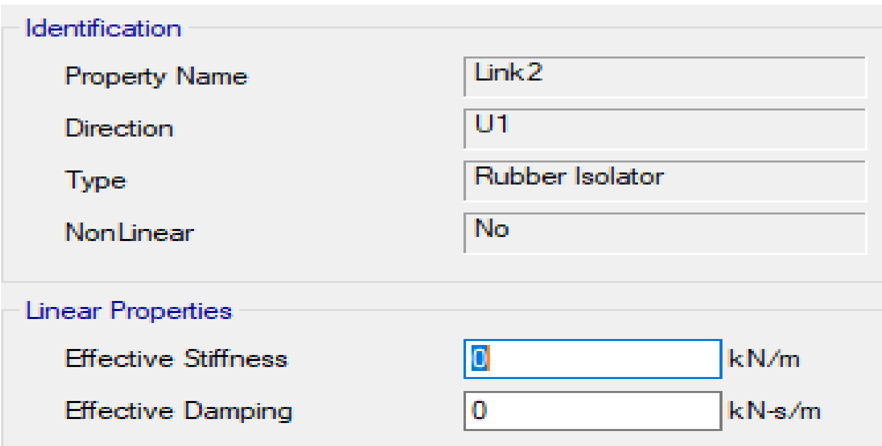

Figure D.2: Defining the isolator properties in U1 Direction (Vertical)

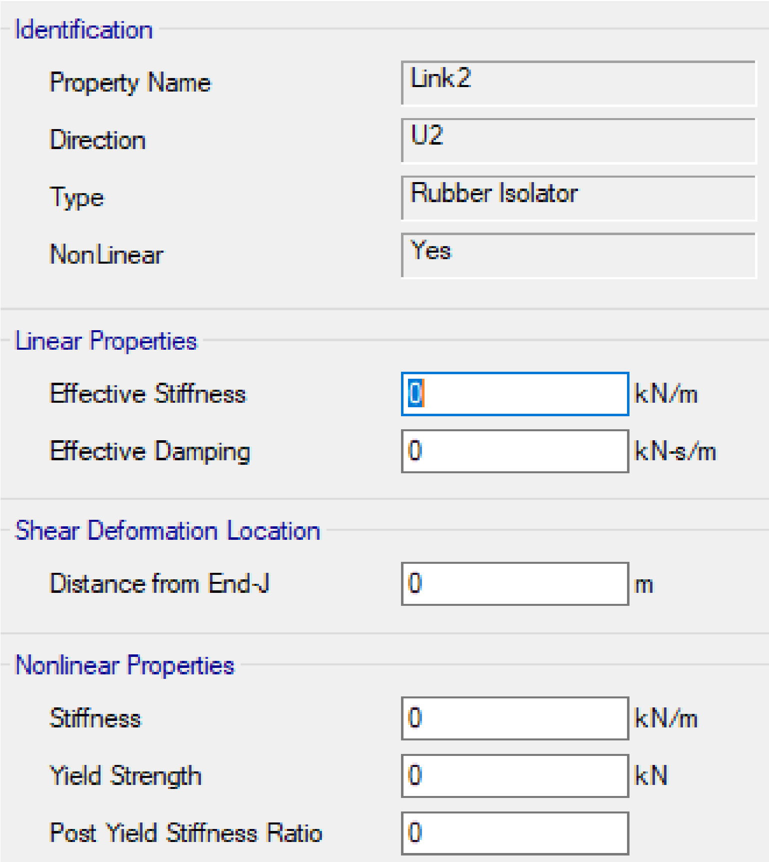

Figure D.3: Defining the isolator properties in U2 and U3 directions (Horizontals)

Friction Isolator bearing

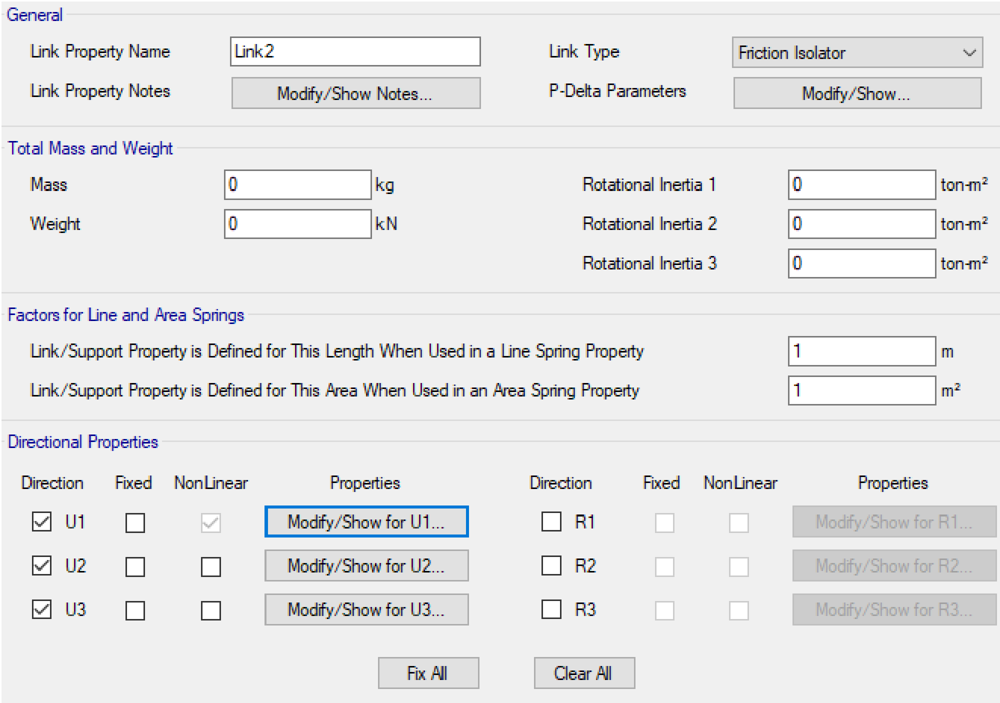

Figure D.4: Defining the isolator link in ETAPS

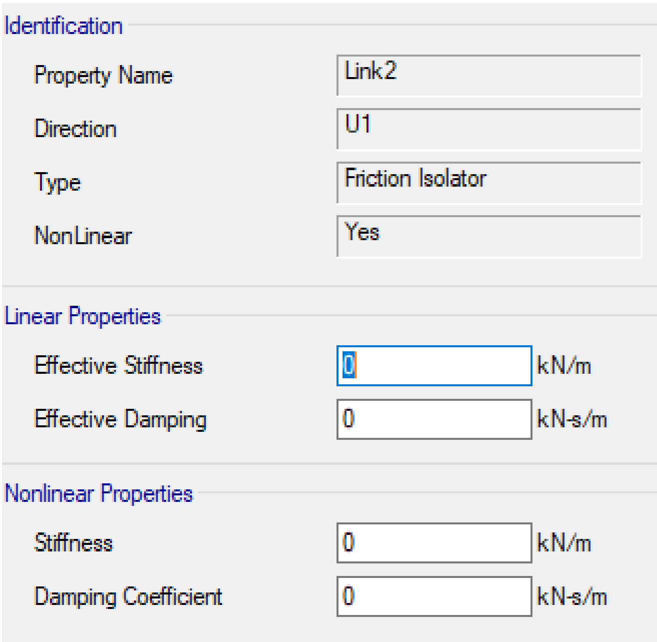

Figure D.5: Defining the isolator properties in U1 Direction (Vertical)

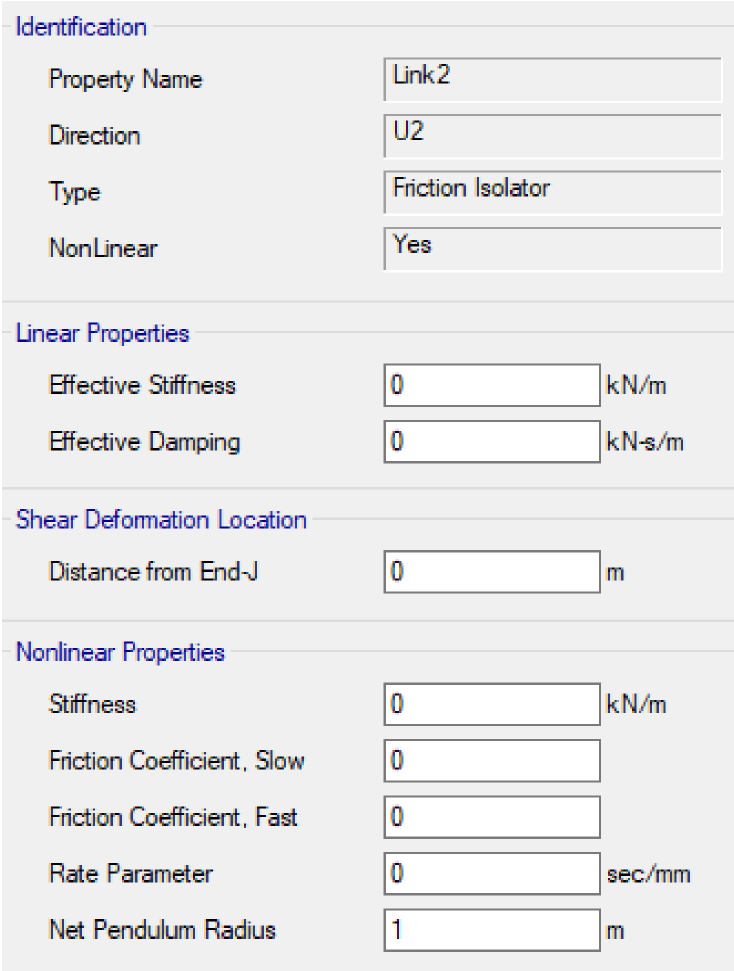

Figure D.6: Defining the isolator properties in U2 and U3 directions (Horizontals)

Appendix E: Beam Reinforcements

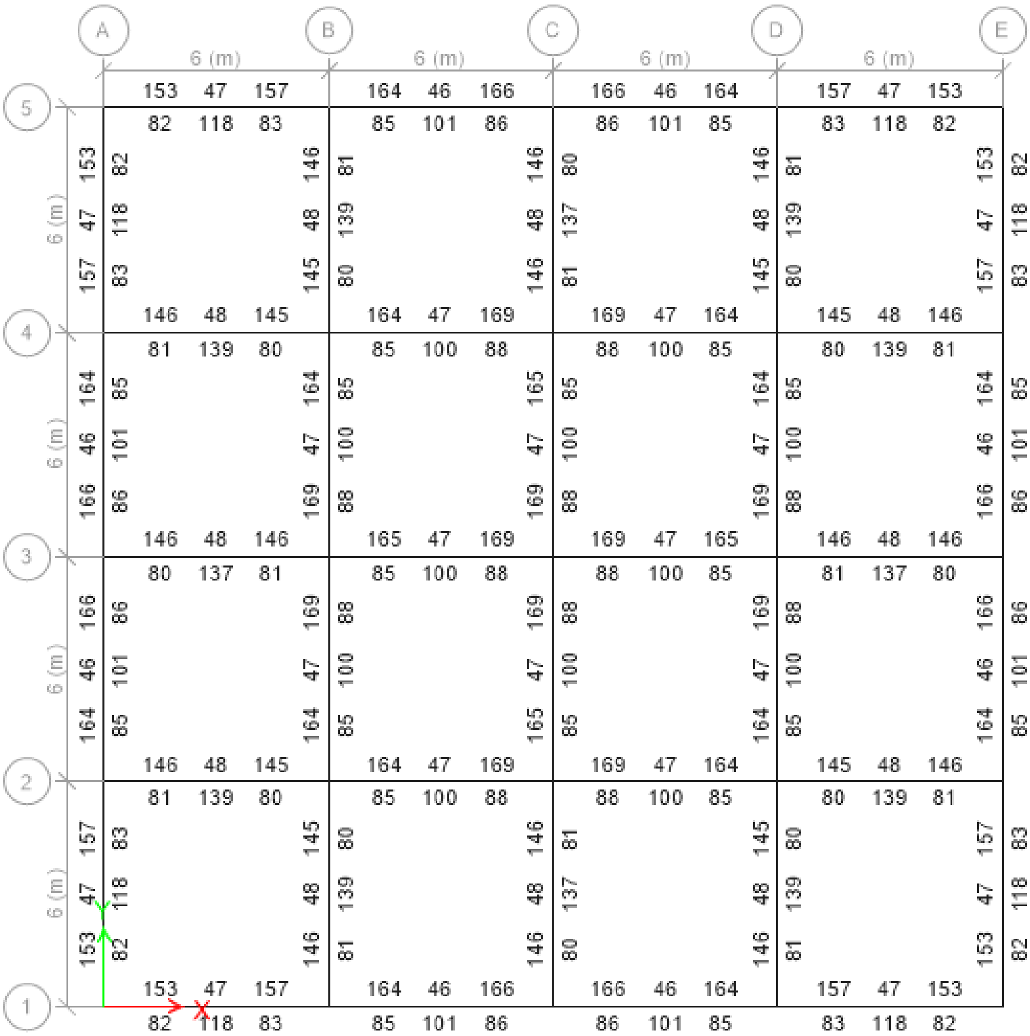

Figure E.1: Beams reinforcements (mm^2) for story 1

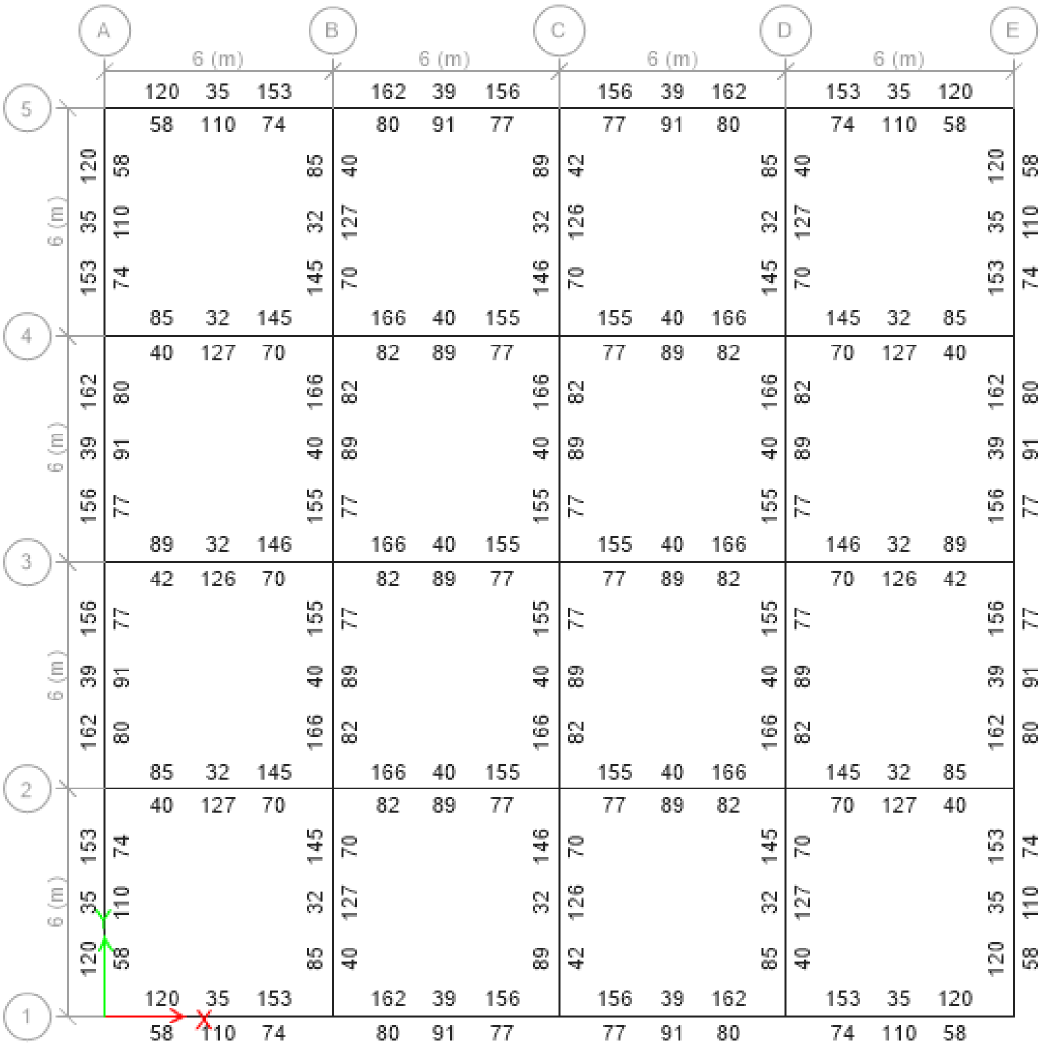

Figure E.2: Beams reinforcements (mm^2) for story 2

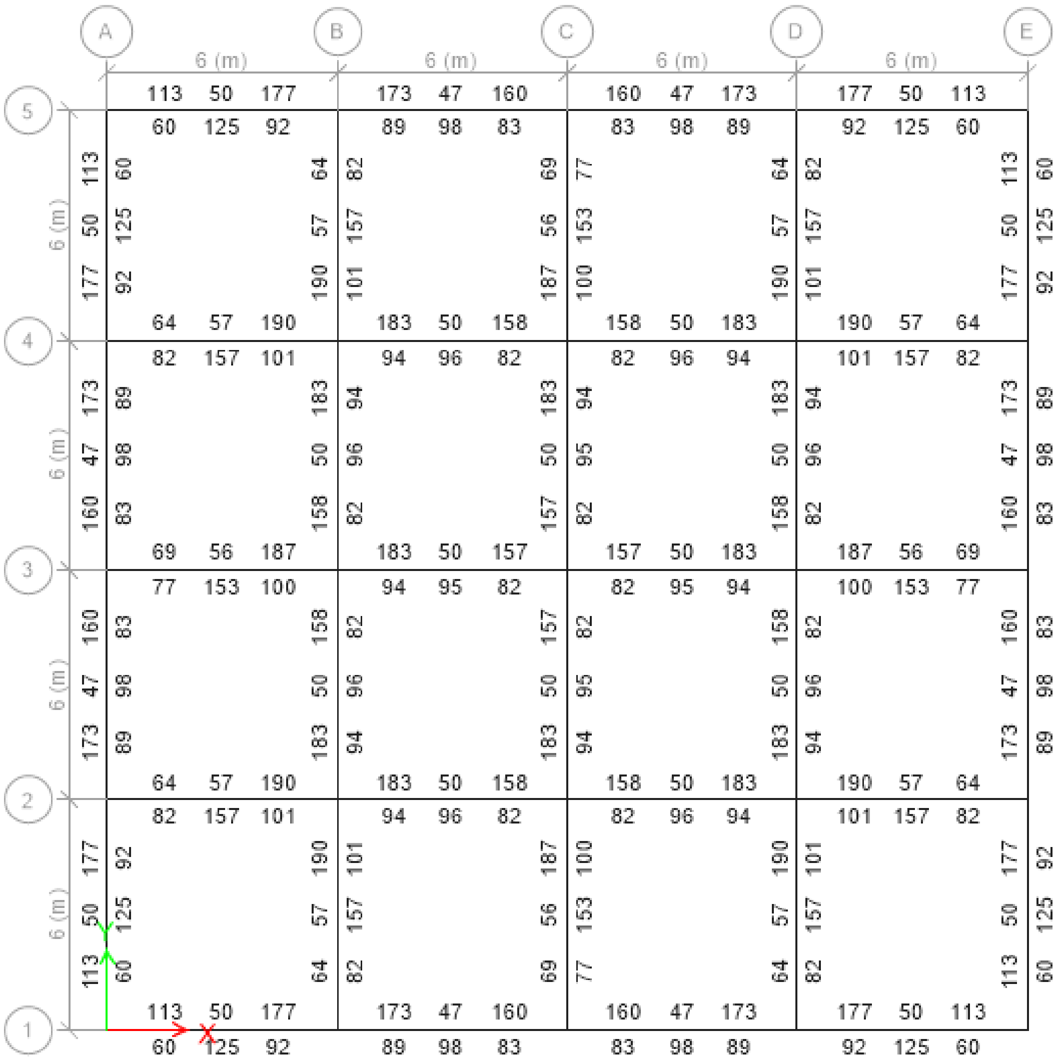

Figure E.3: Beams reinforcements (mm^2) for story 3

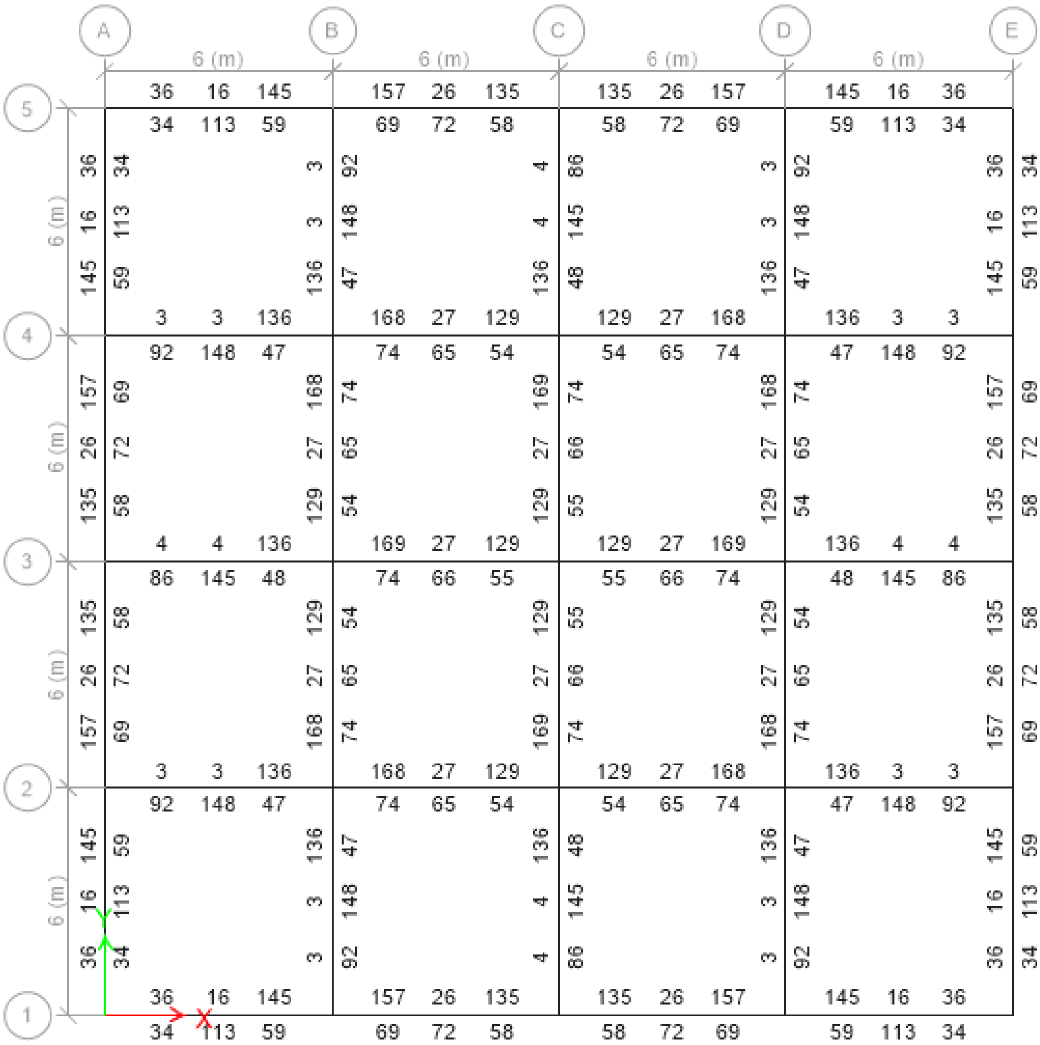

Figure E.4: Beams reinforcements (mm^2) for story 4