Design of Base Isolation Systems for an R.C.C. Building

By

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May 2006

Design of Base Isolation Systems for an R.C.C. Building

Major Project

Submitted in partial fulfillment of the requirements

For the degree of

Master of Technology in Civil Engineering
(Computer Aided Structural Analysis & Design)

By

Dhaval B Sanghani
(04MCL014)

Guide
Prof. S. P. Purohit

DEPARTMENT OF CIVIL ENGINEERING
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May 2006

CERTIFICATE

This is to certify that the Major Project entitled "**Design of Base Isolation Systems for an R.C.C building**" submitted by **Mr. Dhaval B Sanghani (04MCL014)**, towards the partial fulfillment of the requirements for the degree of **Master of Technology in Civil Engineering** (**Computer Aided Structural Analysis and Design**) of Nirma University of Science and Technology, Ahmedabad is the record of work carried out by him is under my supervision and guidance. In my opinion, the submitted work has reached a level required for being accepted for examination. The results embodied in this major project, to the best of my knowledge, haven't been submitted to any other university or institution for award of any degree or diploma.

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ACKNOWLEDGEMENT

It gives me immense pleasure in expressing recognition and profound indebtedness to **Prof. S. P. Purohit**, Assistant Professor, Department of Civil Engineering, Institute of Technology, Nirma University, Ahmedabad, for providing his valued assistance and incessant encouragement & support throughout the Major project. I hereby take an opportunity to acknowledge my indebtedness to him for his continual implication and the clarity of the concepts of the topic that helped me a lot during this study.

I am also thankful to **Mr. Alan Wilson**, Chief Executive Officer, Robinson Seismic Pvt. Ltd. for his continual support and valued assistance in all respects during my study.

I also take the opportunity to thank **Prof. G.N. Patel**, Professor, Department of Civil Engineering and **Prof. P.H. Shah**, Head, Department of Civil Engineering, Institute of Technology, Nirma University, Ahmedabad, for his continual kind words of encouragement and motivation throughout the Major Project. I am thankful to **Prof. C. H. Shah,** structural consultant for his suggestions to improve quality of work. I am also thankful to **Dr. H. V. Trivedi**, Director, Institute of Technology, for his kind support in all respect during my study.

I am thankful to all faculty members of Institute of Technology, Nirma University, Ahmedabad, for their special attention and suggestions towards the project work as and when needed.

I am thankful to God and my family members, the task accomplish wouldn't have been the same without their blessings & moral support.

Last but not least, I am thankful to all my friends, who always supported me and motivated me throughout this course.

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ABSTRACT

Conventional seismic design attempts to make buildings that do not collapse under strong earthquake shaking, but may sustain damage to non-structural elements and to some structural members in the building. This may render the building non-functional after the earthquake, which is not acceptable for important buildings, like hospitals, fire stations, etc. Special techniques are required to design buildings such that they remain practically undamaged even in a severe earthquake. Buildings with such improved seismic performance usually cost more than normal buildings do. However, this cost is justified through improved earthquake performance. One of the technologies used to protect buildings from damaging earthquake effects is “Base Isolation”. The idea behind base isolation is to detach (isolate) the building from the ground in such a way that earthquake motions are not transmitted up through the building, or at least greatly reduced.

The work undertaken is an attempt to understand the fundamentals of Base Isolation, its design & behavior under seismic loading. A RCC building of Basement + GF +4 has been considered with basement constructed of RCC wall at its periphery. As, no specific guidelines are available for design of building with base isolators in Indian code IS 1893-2002 (Part I), IBC 2000 recommendations were used. Three basic types of base isolators namely Lead Rubber Bearing (LRB), High Damping Rubber Bearing (HDR) & Friction Pendulum System (FPS) were designed. The base isolated RCC building was exposed to Design Spectrum seismic loading of IS 1893-2002 (Part I) to compute its response. The conclusions were drawn on the basis of analysis and design of base isolator along with comparison of displacement, storey drift and base shear for fixed base with RCC isolated building. A commonly available, widely used software SAP2000 v 8.08 was utilized as it is available at Computer centre of Civil Engineering Department, Institute of Technology, Nirma University.

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ABBREVIATION NOTATION AND NOMENCLATURE

Symbol	Description
LRB	Lead Rubber Bearing
FPS	Friction Pendulum System
HDR	High Damping Rubber Bearing
D_D	Design displacement, being the displacement at the center of rigidity of the isolation system at the DBE
D_M	Maximum displacement, at the center of rigidity of the isolation system at the MCE
D_{TD}	Total design displacement (DBE)
D_{TM}	Total maximum displacement (MCE)
T_D	Effective isolated period corresponding to DBE
T_M	Effective isolated period corresponding to MCE
B_D	Damping reduction factor for DBE
B_M	Damping reduction factor for MCE
β_D	Effective damping in the system at DBE
β_M	Effective damping in the system at MCE
S_1	The MCE 5% damped spectral acceleration for the site available from the maps accompanying the IBC-2000
S_{D1}	Spectral coefficient corresponding to DBE
S_{M1}	Spectral coefficient corresponding to MCE
V_s	Shear force
V_b	Lateral seismic force
F_x	Lateral force at level x
w_x	Weight at level x
w_i	Weight at level i
h_x	Height of structure above isolation level
h_i	Height of structure above isolation level.
h_{sx}	Story height below level x
δ_{se}	Drift determined by an elastic analysis
δ_x	Drift at any level x
K_{Dmin}	Minimum effective horizontal stiffness of the isolation system at the design displacement (DBE)
K_{Mmin}	Minimum effective horizontal stiffness of the isolation system at the maximum displacement (MCE)
K_{Dmax}	Maximum effective stiffness of the isolation system at the design displacement (DBE)

K_{Mmax}	Maximum effective horizontal stiffness of the isolation system at the maximum displacement (MCE)
R_I	Reduction factor for Base Isolated Structure
g	Gravitational Acceleration
W	The weight of the building
F_v	Site coefficient defined for various site classes and acceleration levels
I_E	Occupancy importance factor for the building.

1. INTRODUCTION

1.1 INTRODUCTION

The field of seismic design is a subject directly concerned with both life safety and cautious and slow to innovate. Like other code-dominated issues, and like airplane safety, seismic safety has never been much of an important issue. In short, seismic safety is generally taken for granted. Improvements in seismic safety, since the time of the San Francisco earthquake of 1906, have been due primarily to acceptance of ever-increasing force levels to which buildings must be designed. Development of structural systems that perform reasonably well, and enable materials such as steel and reinforced concrete is necessary. The choices for lateral resistance lie among shear walls, braced frames, and moment resistant frames.

The codes have mandated steadily increasing force levels, in a severe earthquake a building, if it were to remain elastic, would still encounter forces several times above its designed capacity. This situation is quite different from that for vertical forces, in which safety factors insure that actual forces will not exceed 50% of designed capacity unless a serious mistake has been made. For vertical forces, this is easy to do. But to achieve similar performance for seismic forces, the structure would be unacceptably expensive. This disagreement between seismic demand and capacity is traditionally accommodated by reserve capacity, which includes uncalculated additional strength in the structure and often the contribution of portions and exterior cladding to the strength and stiffness of the building. In addition, the ability of materials such as steel to dissipate energy by permanent deformation—which is called ductility—greatly reduces the likelihood of total collapse.

Modern buildings contain extremely sensitive and costly equipment. These building contents are more costly and valuable than the buildings themselves. Furthermore, hospitals, communication and emergency centers, and police and fire stations must be operational when needed most immediately after an earthquake. Conventional construction can cause very high floor accelerations in stiff buildings and large interstorey drifts in flexible structures as shown in FIGURE 1.1. These two factors cause difficulties in insuring the safety of the building components and contents. Hence, it’s necessary to incorporate a new design approach which will reduce the earthquake forces up to an extent and does not damage the structure.

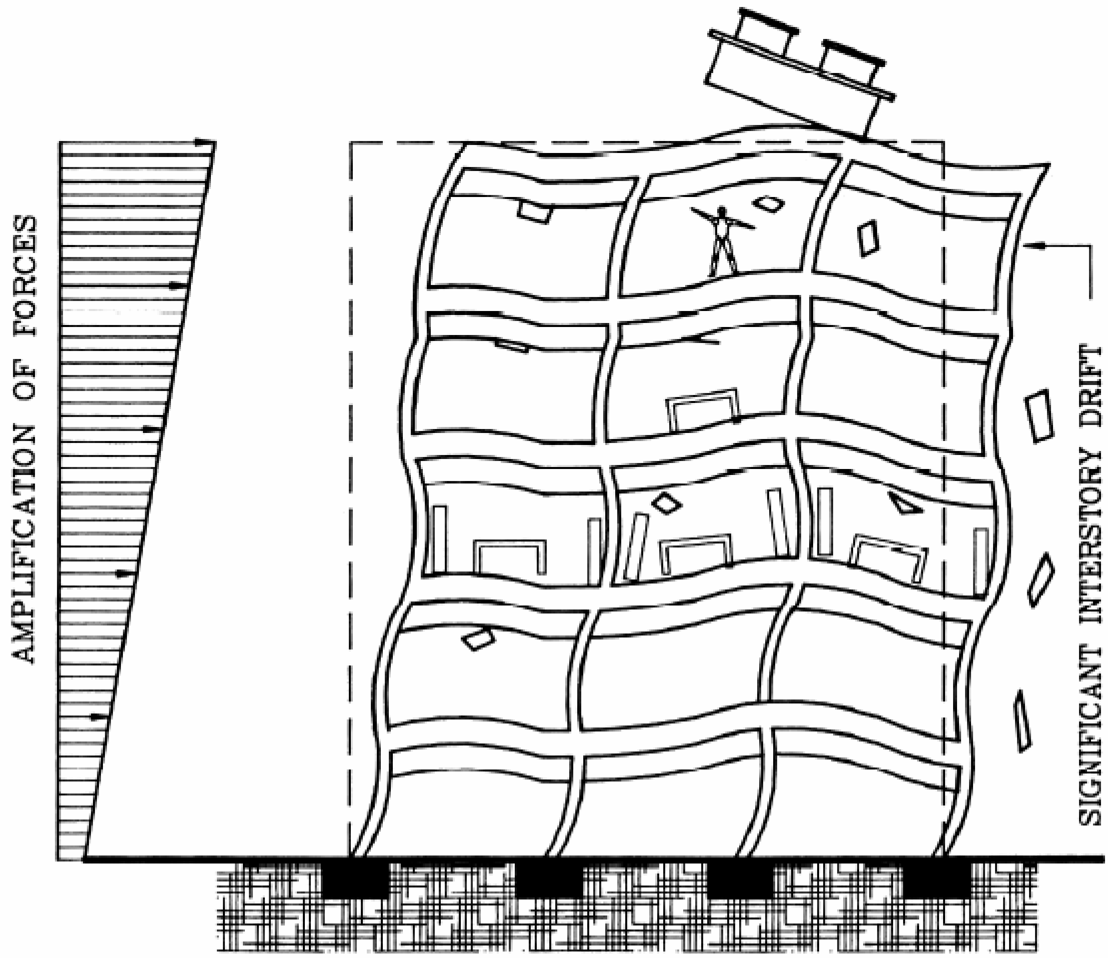


FIGURE 1.1 CONVENTIONAL BUILDING

1.2 BACKGROUND

Conventional seismic design attempts to make buildings that do not collapse under strong earthquake shaking, but may sustain damage to non-structural elements and to some structural members in the building. Hence, it may cause large floor accelerations in stiff buildings and large interstorey drifts in flexible buildings. This may render the building non-functional after the earthquake, which may be problematic in some structures, like hospitals, police & fire stations, etc. which need to remain functional after the earthquake. Hence, special techniques are required to design buildings such that they remain practically undamaged even in a severe earthquake. One basic technology is used nowadays to protect buildings from damaging earthquake effects. This is the Base Isolation technology. The idea behind base isolation is to detach (isolate) the building from the ground in such a way that earthquake motions are not transmitted up through the building, or at least greatly reduced.

The principle of seismic isolation is to introduce flexibility at the base of a structure in the horizontal plane, while at the same time introducing damping elements to restrict the amplitude of the motion caused by the earthquake. Mounting buildings on an isolation system will prevent most of the horizontal movement of the ground from being transmitted to the buildings. This results in a significant reduction in floor accelerations and interstorey drifts, thereby providing protection to the building contents and components as shown in FIGURE 1.2.

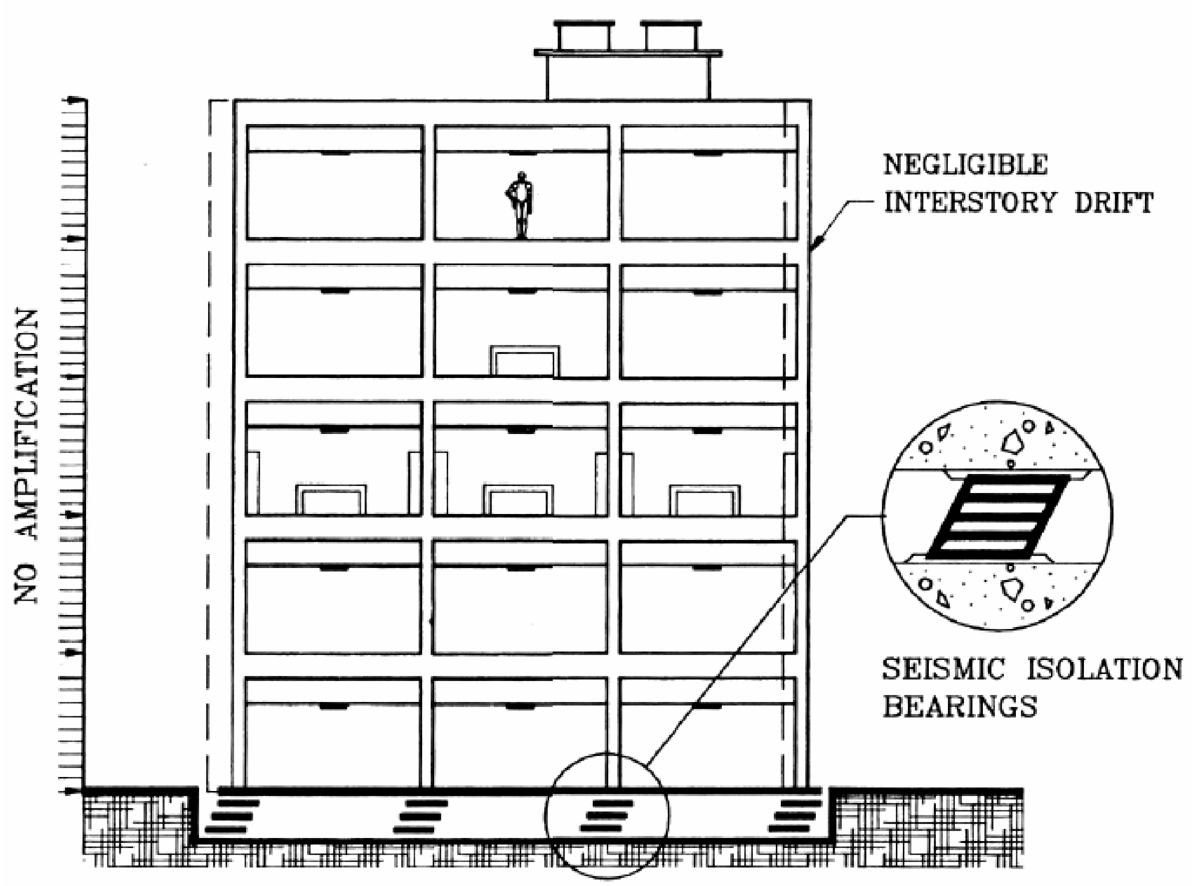


FIGURE 1.2 ISOLATED BUILDING

Importance is given to the concept of seismic isolation by the successful development of mechanical-energy dissipaters and elastomers with high damping properties. Mechanical energy dissipaters, when used in combination with a flexible isolation device, can control the response of the structure by limiting displacements and forces, thereby significantly improving seismic performance. The seismic energy is dissipated in components specifically designed for that purpose, relieving structural elements, such as beams and columns, from energy-dissipation roles (and thus damage).

The advantages of seismic isolation include the ability to eliminate or very significantly reduce structural and nonstructural damage, to enhance the safety of the building contents and architectural facades, and to reduce seismic design forces. These potential benefits are greatest for stiff structures fixed rigidly to the ground, such as low- and medium-rise buildings, nuclear power plants, bridges, and many types of equipment. Some tectonic and soil-foundation conditions may, however, prevent the use of seismic isolation.

1.3 OBJECTIVE OF WORK

With above mentioned background, following objective was derived for the work: -

- Understand the fundamentals of Base Isolation systems for an undertaken R.C.C building.
- Design a suitable Base Isolation system; and
- Comparison of Base Isolated & Non-base Isolated buildings & allied parameters.

1.4 SCOPE OF THE STUDY

Following line of action was decided to fulfill the above mentioned objective.

i. Obtaining response of 3D fixed base RCC building
ii. Defining target parameters
iii. Analysis & Design of base isolation system
iv. Obtaining response of base isolated RCC building
v. Comparison of fixed base & isolated base RCC building

As analysis & design of isolators requires number of parameters, use of computer software is must. A widely used and commercially available software SAP2000 was used for analysis of isolated as well as fixed base RCC building. An Excel spreadsheet was also used for computing designs of isolators mainly Lead Rubber Bearing (LRB), High Damping Rubber Bearing (HDR) & Friction Pendulum System (FPS).

1.5 ORGANIZATION OF WORK

The Major Project is divided into eight chapters. They are as follows: -

Chapter 1 introduces the topic and gives a general view about base isolation, need of present study, objective of work, scope of the study and organization of work.

Chapter 2 deals with the details of literature review of various technical papers, books and journals. This provides references for the analysis & design procedure of different types of bearings & implementation of IBC 2000.

Chapter 3 deals with the fundamentals of base isolation systems; viz. incorporation of the theoretical aspects regarding analysis, suitability of base isolation, its design principles, objective of base isolation, locations of bearings in buildings, types of bearings used and their suitability.

Chapter 4 highlights the use of SAP2000 and its implementation for modeling & dynamic analysis for fixed base RCC building using response design spectrum of IS 1893-2002 (Part-I).

Chapter 5 highlights design of three types of bearings, viz. Lead Rubber Bearing, Friction Pendulum System & High Damping Rubber Bearing as per IBC 2000 provisions.

Chapter 6 highlights the use of SAP2000 and its implementation for modeling & dynamic analysis of base isolated RCC building using response design spectrum of IS 1893-2002 (Part I).

Chapter 7 highlights the comparative results of analysis for fixed & isolated base RCC building in the form of time period, modal mass participation, base shear, displacement & storey drift.

Chapter 8 deals with conclusion of the study and future scope of the work.

2. LITERATURE REVIEW

Many researchers have considered various aspects of ground-borne vibration and its effects on buildings and their occupants, and several detailed studies have already been undertaken. Some of the papers giving thought to Base Isolation of Buildings, Retrofitting of building by Seismic Base Isolation and the study of structural response due to actual earthquake are studied and abstract of the same are presented below. This literature review provides an overview of previous research in this field, with particular emphasis on the work of direct relevance to base-isolated buildings.

Farzad Naeim, Ronald L Mayes [1] presented the principles, benefits and the feasibility of Seismic Isolation. The basic principles of Seismic Isolation were introduced first. Force-deflection characteristics of commonly used Isolation devices are introduced, followed by guidelines for evaluation of the feasibility of Seismic Isolation as an alternative for a given project. The differences in approach to new construction and rehabilitation of existing structures are highlighted. The building code provisions for seismic isolation are covered next. The IBC-2000 design provisions for seismic isolation are discussed in detail. A simple preliminary design procedure is provided to aid engineers in initial sizing of the isolation devices. Several examples are provided to illustrate the practical application of the material covered. The results show that the theory of Seismic Isolation permits substantial cost savings for isolated buildings compared to conventional construction. However, the initial construction cost may exceed the cost for a similarly situated fixed base building by as much 5 %. For the retrofit of buildings, seismic isolation may only be technically applicable in 1 out of approximately 8 buildings.

Yeong-Bin Yang, Kuo-Chun Chang, Jong-Dar Yau [2] presented the philosophy behind Seismic Isolation systems, basic requirements of Seismic Isolation systems and the design criteria for Isolation devices like HDR, LRB & FPS. Example is provided to illustrate the practical application of the design concept and a comparison is carried out for the three types of bearings for the same project. It was concluded by the author that the procedures presented here serve merely as a key concept involved in initial sizing of the base isolation systems. Extra care must be given in applying isolators to the rehabilitation of existing buildings.

Rihui Zhang [3] presented basic concepts, modeling and analysis for an isolated structure. Seismic Isolation and Energy Dissipation devices like elastomeric isolators, sliding isolators and few dampers are presented. This is followed up by performance and testing requirements for isolation devices. Design guidelines and design examples are presented, where the design guidelines follow AASHTO guidelines for bridges and UBC guidelines for buildings. This guideline contains general requirements for isolation, selecting proper isolation device, methods of analysis, design displacement & design force. Recent development in this field and application are presented. The author has made an attempt to introduce the basic concepts of seismic isolation and supplemental energy dissipation devices and their history, current developments, applications, and design related issues.

Fu Lin Zhou, Zheng Yang, Xiang Yun Huang, Ping Tan [9] presented the urgent requirement of using Seismic Isolation in China. Different new concepts of Seismic Isolation that are used in China related to Base Isolation such as story isolation, top isolation and over bridge linking isolation are explained here. Significant advantages of buildings with Seismic Isolation are presented here, followed by the different materials that are used for the isolators in China. Different locations of Isolation layer and different designing levels for Isolation buildings are mentioned. The Technical codes on Seismic Isolation in China are covered next. Several examples are provided to illustrate the practical application of the base isolation. Design, Shaking table test and analysis results are covered next. Also brief introduction to the recent research and development on seismic isolation in China has been presented here. The results of the shaking table test shown that the horizontal acceleration response were decreased to be ¼ for super structural and ½ for platform structure comparing with the traditional anti-seismic structure. The acceleration values from analysis are larger than the acceleration values from testing in most of cases. It means that the analysis could get conservative results.

Sajal Kanti Deb [10] presented 3D non-linear analysis procedure of base isolated building. Important issues related to the design like suitability of seismic isolation, design parameters for bearings and testing requirements for isolators are presented. Shear test for obtaining force-displacement hysteresis loop of isolation bearings is outlined. Other important issues include the effect of soft soil on performance of base isolated building, effects of near fault motion, soil-base isolated building interaction. It was concluded that the effect of soil-structure interaction on modal properties and seismic forces is small when the isolators are much more flexible, than the soil; when the flexibilities of the isolators and soil are comparable, the soil may contribute to the building behavior. From the results of the test carried out for base isolation on soft soil it was shown that the base isolation systems can be used at soft-soil sites where load on the isolation system and, consequently, sizes of the isolation systems are sufficiently large to accommodate the resulting large displacements.

James M. Kelly [11] presented the ideas behind the concept of base isolation. In this approach the building or structure is decoupled from the horizontal components of earthquake ground motion by interposing a layer with low horizontal stiffness between the structure and the foundation. Research and development on the use of natural rubber bearings for Isolating buildings from earthquakes is presented. U.S. applications of base isolation are presented followed by application of base isolation in Japan and finally the application of base isolation for nuclear power plants is presented. From the research work carried out it was proved that research has improved the effectiveness of isolators in decreasing problems of stability, roll-out, failure of isolators, or unexpected response. The difficulties of manufacturing large isolators have diminished. It was now possible to make bearings of large diameters, because of the research work carried out.

Taft Tucker [12] presented a paper on the retrofit of Okuma memorial hall using base isolation retrofit. In this project the author was able to construct a two-dimensional model of the fixed base building for static and dynamic analysis. He also constructed a base-isolation model to evaluate the benefits of a retrofit to the building. For the base-isolated model, he constructed models for passive and semi-active control of the building to evaluate the possibility of using a semi-active control strategy on the building. The objective of this project is to show the possible benefits of the base-isolation retrofit of Okuma Hall, and to evaluate the usefulness of semi-active control versus passive control on the building for a range of earthquake magnitudes. Results show that for the small El Centro earthquake, acceleration is reduced by 90%, and base shear is reduced by 80%. However, base deflection becomes a problem. It is necessary to implement an effective control strategy to the building in order to control deflection without increasing the forces induced in the superstructure.

Michael D Symans, Glenn J Madden, Nat Wongprasert [13] investigates the ability of an adaptive seismic isolation system to protect structures subjected to a variety of earthquake ground motions. The isolation system consists of sliding isolation bearings in combination with an adaptive hydraulic damper. The damping capacity of the hydraulic damper can be modified in real-time to respond to the effects of the earthquake ground motion. The real-time control operations were carried out using a sophisticated data acquisition and control system which allowed for seamless integration of the design and implementation of the control system. The analytical predictions compared reasonably well with the experimental test data. Furthermore, the numerical simulations generally showed that, for a wide variety of earthquake ground motion characteristics, an adaptive sliding base isolation system is capable of simultaneously limiting the response of the isolation system and the superstructure. This study concentrates on the experimental laboratory implementation of the adaptive isolation system within a scale model building structure.

Peter Clark [15] presented the response and behavior of 2 Base Isolated Buildings in the 1994 Hyogoken-Nanbu earthquake. One of the buildings was the largest isolated building in Japan, a six-story steel reinforced concrete computer center with a total floor area of 505,000 square feet (47,000 square meters). The other, approximately 500 meters away, is a three-story reinforced –concrete laboratory with a total floor are of 5,200 square feet (486 square meters). Floor-accelerations in the Base Isolated buildings for different floor levels were presented for both the buildings and from the results it was concluded that the isolation system was very effective in both the cases and there was no damage in the isolated building, but at the roof of the adjacent fixed-base structure there were reports of dropped ceiling tiles and a crack in the ventilation duct.

F.F. Tajirian [16] presented the applications of seismic isolation to civil components, tanks and industrial facilities. The benefits of seismic isolation to such applications as well as differences in design requirements between building and non-building isolation are illustrated through the examples described. It was concluded from the results that the seismic isolation of individual components is very beneficial in situations where existing components and their supports have to qualify for higher seismic loads. The results predict that the use of seismic isolation may possibly avoid expensive retrofitting of the supporting facility and the foundation. Later three examples of this type of retrofit are presented.

Ian G. Buckle et al. [17] presented the seismic retrofitting of New-Zealand Parliament house and library building by base isolation. The building was constructed in 1899 and 1922 respectively. Retrofitting techniques employed included seismic isolation over conventional strengthening techniques and installation of 145 LRB, 230 HDR and 42 FPS bearings. Installation of the isolators required strengthening of basement walls and columns and the provisions of floor diaphragms, re-piling the building with LRB bearings and rubber bearings in the supports, as well as cutting a seismic gap in the 500 mm thick concrete wall. The fundamental period of the building was increased to 2.5 sec from 0.45 sec. It was concluded from the results that the building will be able to move in any direction on a horizontal plane up to distance of 300 mm.

Hideaki Saito et al. [18] reports the result of a study that evaluated the applicability of the seismic isolation system to nuclear power plants. The study focuses on possibilities of a standard design with improved seismic safety of building and equipment for ABWR-II, Advanced BWR-II, located in high seismic intensity areas. Reactor Building was selected for the study since it requires especially high seismic safety and improvement of its design will possibly reduce the construction cost greatly.

A base isolation system with laminated lead rubber bearing was used in the study. Based on the structural design of isolated buildings, it was confirmed that the design seismic loads can be largely reduced and that seismic elements of buildings and equipment can be easily designed compared with non-isolated buildings. Improvement in the building construction cost and period was also confirmed. Seismic probabilistic safety assessments were performed for two reactor buildings, with and without seismic base isolation.
The analytical results showed that an isolated reactor building has a much higher degree of the seismic safety than a non-isolated building, especially in hard rock sites. The study concludes that the seismic isolation system is well applicable to ABWR-II plants. In addition, with an aim to enhance the earthquake-resistance of future ABWR-II plants, a building concept was developed, in which a lot of important equipment are laid out on a floor directly supported by the base isolation system. On this plant, further improvement of the seismic reliability is expected due to reduction of the seismic responses of important equipment.

Masaru Kikuchi et al. [19] proposed an analytical hysteresis model for elastomeric seismic isolation bearings. An extensive series of experimental tests of four types of seismic isolation bearings-two type of high-damping rubber bearings, one type of lead-rubber bearing and one type of silicon rubber bearing was carried out with the objective of fully identifying their mechanical characteristics. The proposed model is capable of well-predicting the mechanical properties of each type of elastomeric bearing into the large strain range. Earthquake simulator tests were also conducted after the loading tests of the individual bearings. In order to show the validity of the proposed model, non-linear dynamic analysis were conducted to simulate the earthquake simulator test results. Good agreement between the experimental and analytical results shows that the model can be an effective numerical tool to predict not only the peak response value but also the force-displacement relationship of the isolators and floor response spectra for isolated structures.

Dr. Roberto Leon [20] investigated the use of base isolation in structures. In existing structures, much of the energy generated through ground motion has to be absorbed and dissipated by the structures through yielding and cracking.

Thus, these buildings sustain a large amount of damage when subjected to a large earthquake. Earlier research has found that if the energy to be absorbed by a structure is reduced, damage can be minimized. The goal of this research is to find out if using base isolation significantly changes the amount of damage the structure experiences. Two buildings were designed and analyzed; one of the structures was pinned at the base and the second structure was base isolated. Findings included a decrease in accelerations of the structure and an increase in the period and displacements. This supports the concept that base isolation reduces the energy that is absorbed by a structure and decreases the damage that is sustained.

Valentin Shustov [21] investigated how well four buildings employing the concept of seismic isolation had survived the 1994 Northridge earthquake. To compare the promise vs. performance, a mathematical model was reduced to SDOF system excited horizontally in accordance with a recorded on a basement real time history. The recording instruments locations in the buildings were mostly random, scanty and they were, arranged in assumption that the superstructure would be rocking like a rigid body. None of the base isolated buildings performed up to expectations. In fact, they performed much worse, namely Los Angeles Fire Command and Control Facility - 3.6 times, USC Hospital - 4.7 times, Los Angeles townhouse - 5.2 times, Rockwell International building (Seal Beach) - 17.0 times. There are at least two of those buildings where the seismic isolation techniques were misused. They performed, correspondingly, 1.3 and 1.8 times worse than their hypothetical non-isolated counterparts.
These are the following major reasons why the existing buildings, which incorporating seismic isolators, performed below the expectations during the recent earthquakes: 1. Predictions of their earthquake performances were made in assumption of the whole building structure acting as an absolutely rigid body rocking on their seismic isolators, while the higher natural modes of vibration were, practically, neglected. 2. Possibility of a negative effect of a heavy damping mechanism of those isolators, that could generate short pulses of a high intensity, was overlooked. 3. The buildings that were erected on seismic isolators remained essentially resonant systems in a wide range of earthquake frequencies.

The results of this investigation cast serious doubts on the ability of the current base isolation research and engineering to predict accurately actual performances of the buildings targeted for earthquake protection and, which is even more important, to make this technology work. At the same time, two base isolated buildings that experienced a considerable shaking during the 1995 Kobe earthquake, namely, the West building in the Ministry of Post and Telecommunications of Japan complex and the Research building of the Matsumuragumi Technical Laboratory, performed quite well.

Ian D. Aiken et al. [22] presented earthquake simulator tests of 1/2.5 scale model of an existing base isolated, three-story reinforced concrete building in Japan. The building is one of a pair of buildings, one isolated and one fixed base that were constructed to evaluate the effectiveness of seismic isolation. The earthquake simulator test consisted of four phases. In the first phase component tests of three different types of elastomeric isolation bearings were performed. In the second phase, the building was tested on each isolation system in turn, to obtain direct comparisons of their performance. Two types of HDR isolators and one type of LRB isolator were used in these tests, and bracing attached to the model to prevent damage to the concrete superstructure. In the third phase, the unbraced model was subjected to a wide range of earthquake inputs, this time with only one type of HDR bearings. The most important tests in this phase were extreme earthquake inputs, sufficiently severe to cause substantial inelastic action on the superstructure and nonlinear stiffening behavior in the bearings. The final phase involved epoxy-injection repair of the concrete frame, and then moderate-level tests of the model in both isolated and fixed-base conditions.
Results from the shake table tests show significant reductions in superstructure accelerations, interstorey drifts, and base shear forces due to the isolation systems, when compared with the expected response of the equivalent fixed-base building.

Gloria Shin [23] in this study presented a method to remotely identify structural properties of buildings using parametric models. Numerical analysis was conducted using data obtained from one of the base isolated structures at Keio University in Japan. With a help of advanced computing software, the unknown parameters in a model were estimated using the available data. The obtained parametric models were then used to identify natural frequencies and damping ratios of the structure. The results of this study showed that proper parametric models are capable of accurately identifying the structural properties. Therefore, labor intensive and time consuming physical inspection to monitor health of the structures can be avoided using mathematically based parametric identification methods.

Ian D. Aiken **[24]** presents important characteristics of isolation devices and the influence of these characteristics on testing, in terms of such factors as displacement, force, rate of loading, and test temperature. The practical limitations of both institutional and manufacturers testing facilities are discussed in terms of theoretical test force, displacement, and velocity requirements. Various design code guideline documents also address energy dissipation devices and associated testing requirements. A growing interest in viscous and visco-elastic damping devices in particular, has highlighted the practical limitations of testing these types of devices. In this work discussion on the specific challenges related to testing highly rate-dependent devices, and factors to be considered in developing realistic test programs is done. The author intends to provide engineers who are involved with or contemplating an isolation or energy dissipation project a context for defining a realistic and practical testing program for the devices that will be part of their project. By way of example, several recent testing programs are described, including the testing of isolation bearings for a new hospital building, the pre-qualification testing of viscous dampers for the retrofit of the Golden Gate Bridge, and the testing of visco-elastic dampers for a building retrofit.

3. BASE ISOLATION SYSTEMS

3.1 FUNDAMENTALS OF BASE ISOLATION

- Principle of Base Isolation

The principle of Seismic Isolation is to introduce flexibility at the base of a structure in the horizontal plane, while at the same time introducing the damping elements to restrict the amplitude of the motion caused by the EQ. The system operates by decoupling the structure from the horizontal components of earthquake ground motion by interposing a layer of low horizontal stiffness between structure and foundation. By using Isolators the building is "decoupled" from the ground motion of any earthquake and the transmission of seismic energy to the building is dampened. This is done by lowering the vibrational frequency, allowing the building to move or displace, and lowering the shock acceleration of the seismic event thus reducing the tendency for the upper floors to move faster than the lower floors.

- Objective of Base Isolation

The objective of seismic isolation systems is to decouple the building structure from the damaging components of the earthquake input motion, i.e. to prevent the superstructure of the building from absorbing the earthquake energy. The entire superstructure must be supported on discrete isolators whose dynamic characteristics are chosen to uncouple the ground motion. Some isolators are also designed to add substantial damping. Displacement and yielding are concentrated at the level of the isolation devices, and the superstructure behaves very much like a rigid body.

Commonly used isolation systems are:

1. Laminated rubber (or elastomeric) bearings and
2. Sliding isolation systems.

Laminated rubber bearings are used with passive dampers for control of excessive base displacement. Laminated rubber bearings with inherent energy dissipation capacities are also developed. Lead rubber bearings and high damping rubber bearings are examples of this category of isolation system.

Sliding bearings mainly utilize Teflon-stainless steel, flat or spherical interface. Sometimes separate elements are provided for recentering of the isolated system.

Three different types of base isolator systems are discussed in brief as follows: -

1. Lead Rubber Bearing

Laminated Rubber Bearings are able to supply the required displacements for isolation. Combining these with a lead-plug insert which provides hysteretic energy dissipation, the damping required for a successful seismic isolation system can be incorporated. Thus the bearing is able to support the structure vertically, to provide the horizontal flexibility together with the restoring force, and to provide the required hysteretic damping.

LRB are usually made of alternating layers of steel plates and natural rubber with a critical hole into which the lead core is press-fitted. When subjected to lateral shear forces, the lead core deforms almost in pure shear, yields at low level of shear stresses, approximately 8 to 10 MPa at normal (20°C) temperature, and produces rather stable hysteretic deformation behavior over a number of cycles. One feature of the lead core is that it can recrystallize at normal temperature and will not encounter the problem of fatigue under cyclic loadings. FIGURE 3.1 shows a typical diagram of LRB with its different properties.

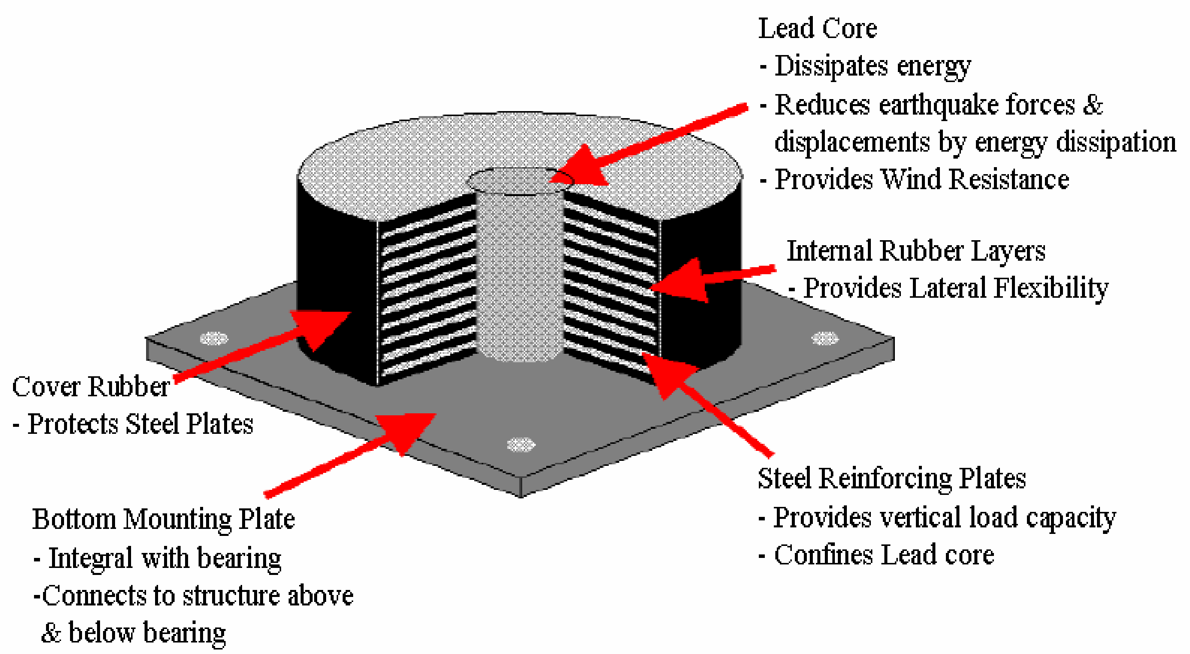


FIGURE 3.1 LEAD RUBBER BEARING

2. High Damping Rubber Bearings

As shown here in FIGURE 3.2 high damping rubber bearings are similar in shape to the elastomeric bearing, except that it is made of specially compounded rubber layers that are usually made of materials that are highly nonlinear in terms of shear strains. Effective damping in the range of 0.10~0.20 of critical can easily be exhibited by the HDR, which is achieved through addition of special chemical compounds that can change the material properties of the rubber. The stiffness and damping of the HDR are required to be large enough to resist wind and minor earthquakes.

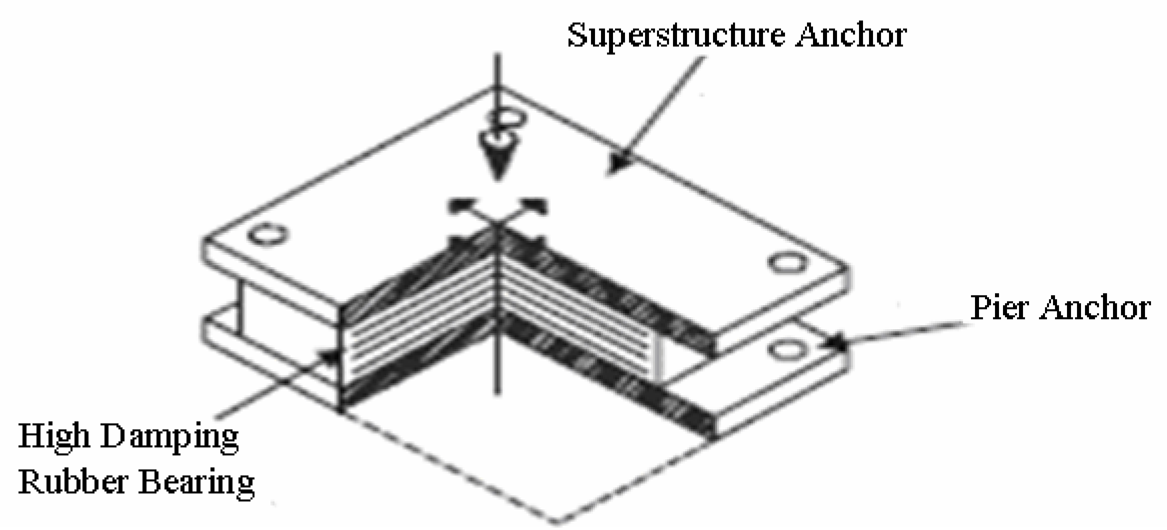


FIGURE 3.2 HIGH DAMPING RUBBER BEARING

3. Friction Pendulum System

One approach for increasing flexibility in a structure is to provide a sliding or friction surface between the foundation and the base of the structure. One particular problem with a sliding structure is the residual displacements that occur after major earthquakes. To remedy this problem, the sliding surface is often made concave so as to provide a recentering force. This is the idea behind the friction pendulum system (FPS), which utilizes a spherical concave surface. To guarantee that a sliding structure can return to its original position, other mechanisms, such as high-tension springs and elastomeric bearings, can be used as an auxiliary system. Sliding Isolation systems have been successfully used for nuclear power plants, emergency fire water tanks, large chemical storage tanks, and other important structures. FIGURE 3.3 shows a typical diagram of FPS.

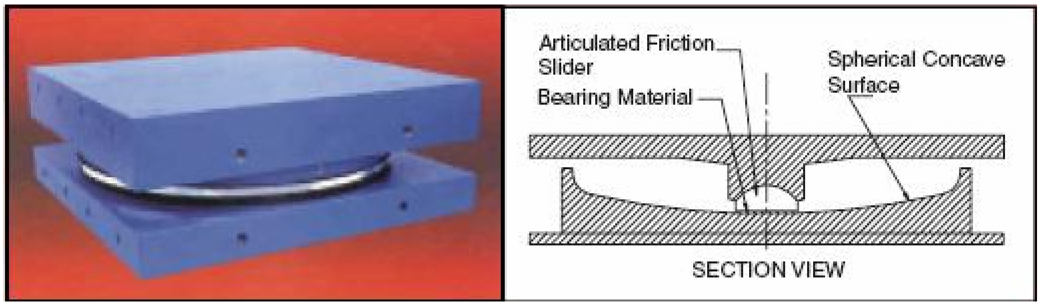


FIGURE 3.3 FRICTION PENDULUM SYSTEMS

- Suitability of Base Isolation

Earthquake protection of structures using base isolation technique is generally suitable if the following conditions are fulfilled:

1. The subsoil does not produce a predominance of long period ground motion.
2. The structure is fairly squat (Be close to the earth, or be disproportionately wide) with sufficiently high column load.
3. The site permits horizontal displacements at the base of the order of 200 mm or more.
4. Lateral loads due to wind are less than approximately 10 % of the weight of structure.

- Basic requirements of Base Isolation

A practical Base Isolation system should meet the following requirements: -

1. Sufficient horizontal flexibility to increase the structural period, except for very soft soils.
2. Sufficient energy dissipation capacity to limit the displacements across the isolators to a practical level.
3. Adequate rigidity to make the isolated building no different form a fixed base building under general service loading.

Most commonly used seismic isolating system can satisfy all the above requirements. However, if the seismic isolating system can be equipped with additional fail safe devices like dampers, then the system will most like be satisfactory.

- Basic Elements of Base Isolation System

There are three basic elements in any practical Seismic Isolation system. They are: -

1. A Flexible mounting so that the period of vibration of the total system is lengthened sufficiently to reduce the force response.
2. A damper or energy dissipater so that the relative deflections between the building & ground can be controlled to a practical design level; and
3. A means of providing rigidity under low load levels such as wind and minor EQ.

- Location of Isolation Layer in building

Figures 3.4 to 3.10 provide typical locations of isolation layers in buildings with and without basement levels. Some of the advantages and disadvantages associated with each layout are listed here. The following general guidelines are considerations for determining a suitable layout:

a. The bearing location should permit access for inspection and replacement.
b. A full diaphragm above or below the isolators to distribute lateral loads uniformly to each bearing is preferable. If distribution is by tie beams only, the bearings should be arranged in proportion to the lateral load taken by each element, i.e., larger bearings under stiffer elements.

– Free movement for the maximum predicted horizontal displacement must be available.

– A layout which allows stub walls or columns as a backup system for vertical loads should be used wherever possible.

– Consideration must be given to the continuity of services, stairways, and elevators at the plane of isolation.

– Consideration must be given to details for cladding if it will extend below the plane of isolation.

Taking in to considerations the above points the different locations of isolation layer that are generally used in the buildings are as follows;

1. Base Isolation: - Isolation layer is located on the base of building.

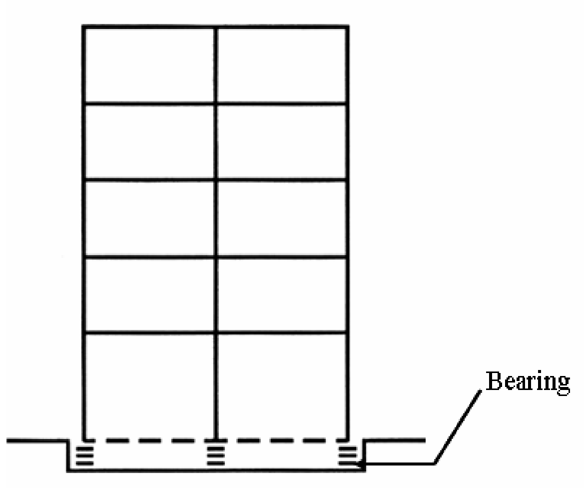


FIGURE 3.4 BASE ISOLATION

Advantages:

a. Minimal added structural costs.
b. Separation at the level of base is easy to incorporate.
c. Base of Columns may be connected by diaphragm.
d. Easy to incorporate back-up systems for vertical loads.

Disadvantage:

a. May require cantilever pit.

2. Basement Isolation: - Isolation layer located on the certain story of the basement.

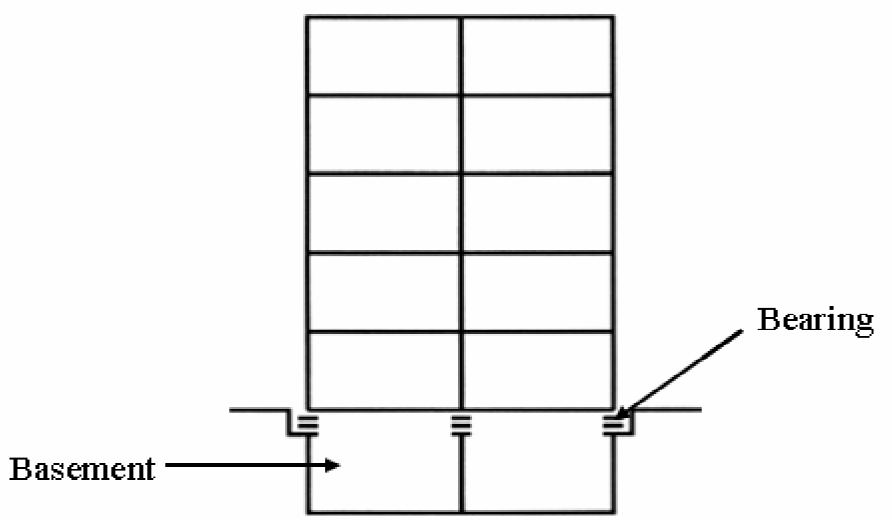


FIGURE 3.5 BASEMENT ISOLATION

Advantages:

a. No Sub-basement required.
b. Minimal added structural costs.
c. Base of columns connected by diaphragm at isolation level.
d. Back-up system for vertical loads provided by columns.

Disadvantage:

a. May require cantilevered elevated shaft below first floor level.
b. Special treatment required for internal stairways below first floor level.

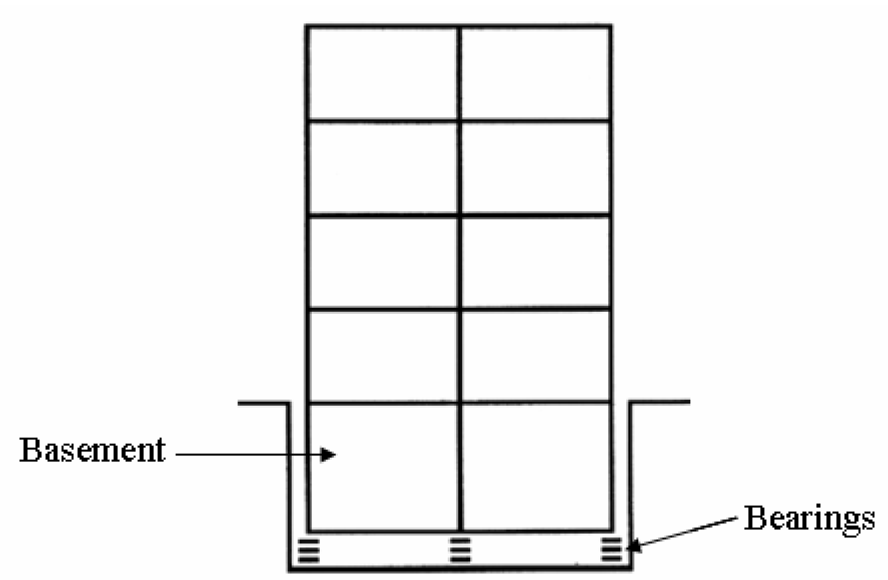


FIGURE 3.6 LOCATION OF BEARING IN SUB-BASEMENT

Advantages:

a. No special detailing required for separation of internal services such as elevator and stairways.
b. No special cladding separation details.
c. Base of columns connected by diaphragm at isolation level.
d. Simple to incorporate back-up system for vertical loads.

Disadvantages:

a. Added structural costs unless sub-basement required for other purposes.
b. Requires a separate retaining wall.

3. Story Isolation: - Isolation layer is located on the top of the first story or certain storey of super structure.

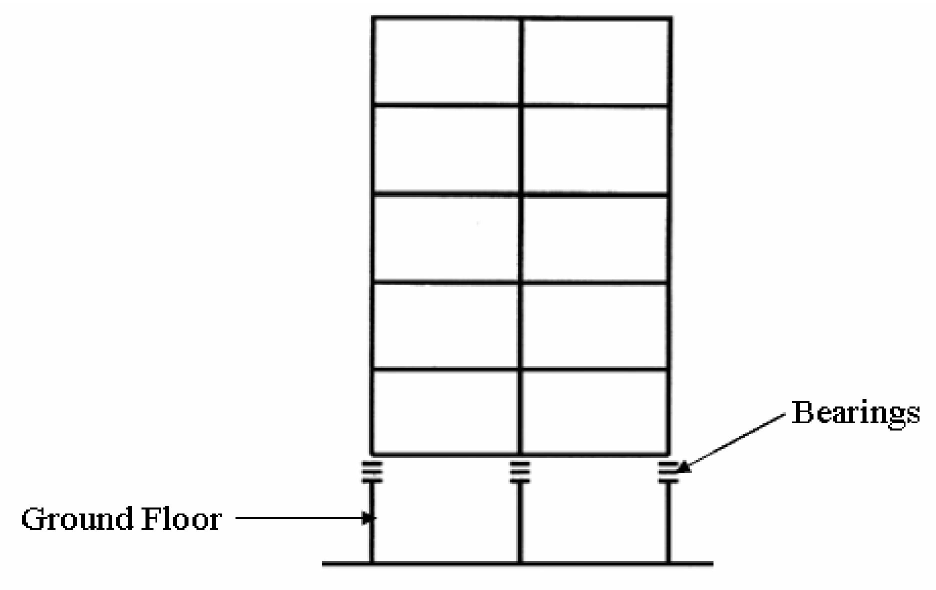


FIGURE 3.7 ISOLATOR LOCATED ON TOP OF GROUND STOREY COLUMN

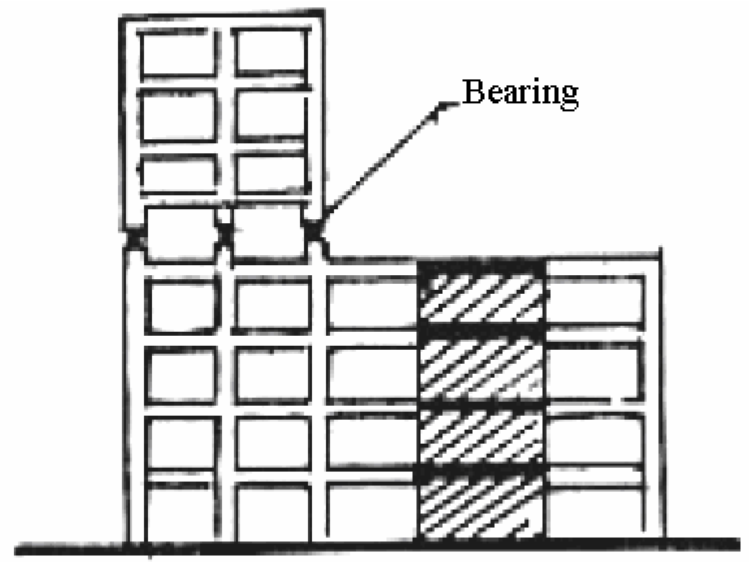


FIGURE 3.8 ISOLATOR LOCATED ON TOP OF CERTAIN STOREY

Advantages:

a. Minimal added structural costs.
b. Economic if first level is for parking.
c. Back-up system for vertical loads provided by columns.

Disadvantages:

a. Special detail required for elevators and stairs.
b. Special cladding details required if first level is not open.
c. Special details required for vertical services.

4. Top Isolation: - Isolation layer is located on the top of the building. It is always used to add 1-2 stories on the top of existing building for seismic retrofit.

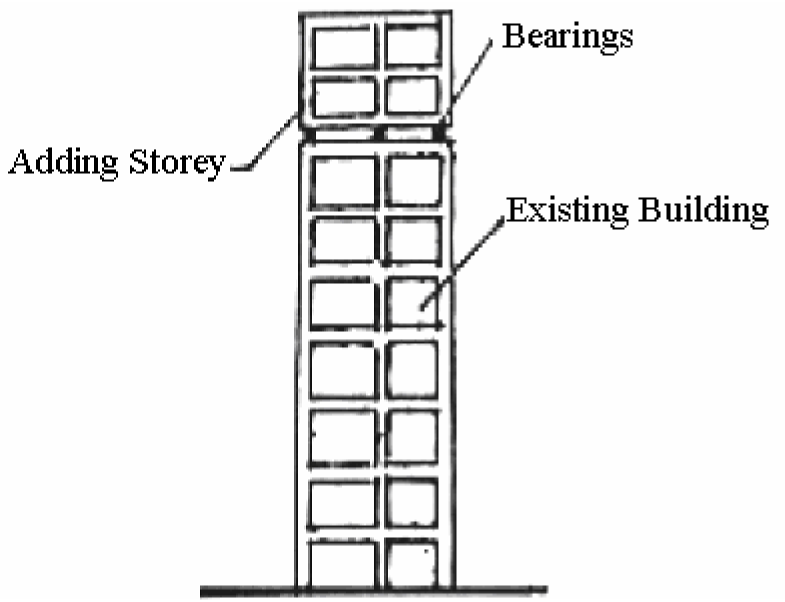


FIGURE 3.9 TOP ISOLATION

5. Over bridge linking Isolation: - Isolation layer is located at the linking joints between over bridge and buildings to decouple the different model shapes of buildings linked by over bridge.

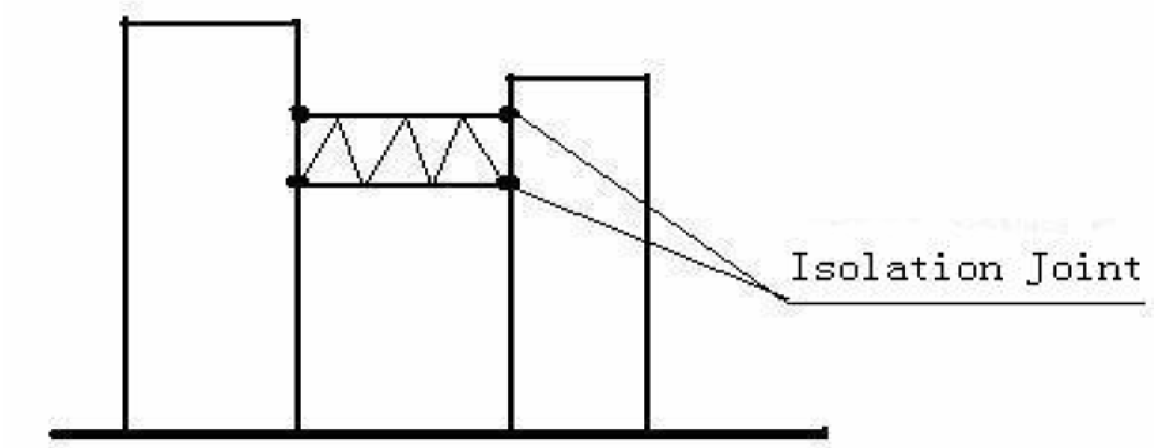


FIGURE 3.10 OVER BRIDGE LINKING ISOLATION

3.2 DESIGN CODE REQUIREMENTS

IBC-2000 is primarily intended to regulate the design of new buildings and it does not cover the retrofit of existing buildings using isolation, although most retrofit projects do follow either the IBC or UBC regulations. IBC-2000 regulations are nonspecific with respect to isolation systems. No particular isolation systems are identified as being acceptable, but the regulations require that any isolation system should be stable for the required displacement, provide increasing resistance with increasing displacement, and have properties that do not degrade under repeated cyclic loading.

The underlying philosophy is that an isolated building designed using IBC-2000 will out-perform fixed-base construction in moderate and large earthquakes. It is not the intent of the code to reduce the construction cost but to minimize damage to isolated structures and their contents.

The seismic upgrade design of existing structures is influenced by the NEHRP Guidelines for the Seismic Rehabilitation of Buildings (FEMA-273) and its commentary (FEMA- 274), which are published by the Federal Emergency Management Agency. FEMA-273 provisions are very similar to those of the IBC-2000 with one exception: FEMA-273 permits a new analysis approach called Static Nonlinear Analysis or the "Pushover" method.

The seismic criteria adopted by current model codes involve a two-level approach to seismic hazard, which are as follows:

1. The Design Basis Earthquake (DBE): That level of ground shaking that has a 10% probability of being exceeded in 50 years (475 year-return period earthquake).
2. The Maximum Considered Earthquake (MCE): The maximum level of ground shaking that may ever be expected at the building site. MCE is taken as 2% probability of being exceeded in 50 years (2500-year return period earthquake).

This is different from UBC-97 definition of MCE which was 10% probability of being exceeded in 100 years (1000-year return period earthquake).

3.2.1 Design Methods

Following methods are used according to the design requirements for a given project.

- Static Analysis

For all seismic isolation designs it is necessary to perform a static analysis. This establishes a minimum level for design displacements and forces. The static analysis is also useful both for preliminary design of the isolation system and the structure when dynamic analysis is required and for design review; under certain circumstances it may be the only design method used. Static analysis alone will suffice if:

1. The structure is located at a site with $S_1 < 0.60g$. S_1 is determined using the spectral acceleration maps published as a part of IBC-2000.
2. The site soil is classified as Class A, B, C, or D.
3. The structure above the isolation plane is not more than four stories or 65 feet in height.
4. The effective period at maximum displacement of the isolated system, T_M, does not exceed 3.0 seconds.
5. The effective period at design displacement, T_D, is greater than three times the elastic, fixed-base period of the structure.
6. The structural system above the isolation plane is regular.
7. The effective stiffness of the isolation system at design displacement is greater than one third of the effective stiffness at 20% of design displacement.
8. The isolation system can produce the restoring force requirements mandated by the code (IBC-2000 Sec. 1623.5.1.4).
9. The force deflection characteristics of isolation system are independent of rate of loading, vertical load, and bilateral load.
10. The isolation system does not limit MCE displacements to less than S_{M1}/S_{D1} times the total design displacements.

Dynamic analysis may be used in all cases and must be used if the requirements mentioned for adequacy of static analysis are not satisfied. Dynamic analysis may take the form of response spectrum analysis or time-history analysis. Response spectrum analysis would suffice if requirements number 2 and 7-10 as mentioned for static analysis, are satisfied. Otherwise, a time-history analysis will be required. Use of more than 30% critical damping is not permitted in response spectrum analysis even if the system is designed to provide for more. Regardless of the type of dynamic analysis to be performed a site-specific design spectra corresponding to DBE and MCE events must be developed and used instead of the code published default spectra if:

1. The structure is located on a Class E or F site, or
2. The structure is located at a site with $S_1 < 0.60g$.

If time history analysis is to be performed, then a suite of representative earthquake ground motions must be selected that satisfy the following requirements:

1. At least three pairs of recorded horizontal ground motion time-history components should be selected and used.
2. The time histories should be consistent with the magnitude, fault distance, and source mechanisms that control the DBE and/or MCE events.
3. If appropriate recorded time-histories are not available, appropriate simulated time histories may be used to make up the total number of required records.
4. For each pair of horizontal ground motion components, the square root sum of the squares (SRSS) of the 5 percent-damped spectrum of the scaled horizontal components is to be constructed.
5. The time-histories are to be scaled such that the average value of the SRSS spectra does not fall below 1.3 times the 5 percent damped design spectrum (DBE or MCE) by more than 10 percent over a range of $0.5T_D$ to $1.25T_M$ where T_D and T_M are effective isolated periods at design displacement and maximum displacement, respectively.
6. Each pair of time histories is to be applied simultaneously to the model considering the most disadvantageous location of mass eccentricity. The maximum displacement of the isolation system is to be calculated from the vectorial sum of the two orthogonal components at each time step.
7. The parameters of interest are calculated for each time-history analysis. If three time history analyses are performed, then the maximum response of the parameter of interest is to be used for design. If seven or more time histories are used, then the average value of the response parameter of interest may be used.

This formulation contains implicit recognition of the crucially important fact that design spectra are definitions of a criterion for structural analysis and design and are not meant to represent characteristics of a single event.

3.2.2 Minimum Design Displacements

Four distinct displacements calculated using simple formulas and used for static analysis, also serve as the code permitted lower bound values (subject to some qualification) for dynamic analysis results. These are:

a. D_D: the design displacement, being the displacement at the center of rigidity of the isolation system at the DBE;

b. D_M: the displacement, at the center of rigidity of the isolation system at the MCE;

c. D_{TD}: the total design displacement, being the displacement of a bearing at a corner of the building and includes the component of the torsional displacement in the direction of $D_{D;}$

d. D_{TM}: same as D_{TD} but calculated for MCE.

D_D and D_M are simply spectral displacement values calculated assuming constant spectral velocity from code published spectral maps and adjusted for damping.

$$D_D = \left(\frac{g}{4\Pi^2}\right)\frac{S_{D1}T_D}{B_D} \tag{1}$$

$$D_M = \left(\frac{g}{4\Pi^2}\right)\frac{S_{M1}T_M}{B_M} \tag{2}$$

where, g is the gravitational acceleration, $S_{D1}$and S_{M1} are spectral coefficients, T_D and T_M are isolated periods, and B_D and B_M are damping coefficients corresponding to the DBE and MCE level responses, respectively.

S_{D1} and S_{M1} are functions of two parameters:

1. S_1, the MCE 5% damped spectral acceleration for the site available from the maps accompanying the IBC-2000; and
2. F_v, the site coefficient defined for various site classes and acceleration levels.

Such that,

$$S_{M1} = F_V S_1 \tag{3}$$

$$S_{D1} = \frac{2}{3} S_{M1} \tag{4}$$

The effective damping in the system, β, at the DBE and MCE response levels (referred to as β_D and β_M are computed from

$$\beta_D = \frac{1}{2\Pi} \left(\frac{total\ area\ of\ hysteresis\ loop}{K_{D,\max} D_D^2} \right) \tag{5}$$

$$\beta_M = \frac{1}{2\Pi} \left(\frac{total\ area\ of\ hysteresis\ loop}{K_{M,\max} D_M^2} \right) \tag{6}$$

where, $K_{D,max}$ and $K_{M,max}$ are effective stiffness terms. The damping reduction factors B_D for the DBE and B_M for the MCE are given in a tabular form (IBC-2000, Table 1623.2.2.1), with linear interpolation to be used for intermediate values. A very close approximation to the table values is given by Naeim and Kelly as

$$\frac{1}{B} = 0.25\,(1 - In\beta) \tag{7}$$

where, β is given as the fraction of critical damping (not as a percentage).

3.2.3 Effective Isolated System Periods

The effective isolated periods T_D and T_M corresponding to the DBE and MCE response are computed from

$$T_D = 2\Pi \sqrt{\frac{W}{K_{D\min} g}} \tag{8}$$

$$T_M = 2\Pi \sqrt{\frac{W}{K_{M\min} g}} \tag{9}$$

where, W = the weight of the building;

g = gravity;

K_{Dmin} = minimum effective horizontal stiffness of the isolation system at the design displacement (DBE);

K_{Mmin}= minimum effective horizontal stiffness of the isolation system at the maximum displacement (MCE).

The values of K_{Dmin} and K_{Mmin} are not known during the preliminary design phase. The design procedure will begin with an assumed value which is obtained from previous tests on similar components or by using the material characteristics and a schematic of the proposed isolator. After the preliminary design is satisfactorily completed, prototype isolators will be ordered and tested, and the values of K_{Dmin}, K_{Dmax}, K_{Mmin}, and K_{Mmax} will be obtained from the results of the prescribed program of tests on the prototypes.

The total design displacements, D_{TD} and D_{TM} (which include torsion), are

$$D_{TD} = D_D\left(1 + y\frac{12e}{b^2 + d^2}\right) \tag{10}$$

$$D_{TM} = D_M\left(1 + y\frac{12e}{b^2 + d^2}\right) \tag{11}$$

where, b and d are plan dimensions at the isolation plane, e is the actual eccentricity plus 5% accidental eccentricity and y is the distance to a corner perpendicular to the direction of seismic loading.

3.2.4 Design Forces

The superstructure and the elements below the isolation interface are designed for forces based on the DBE design displacement, D_D.

The isolation system, the foundation and structural elements below the isolation system must be designed to withstand the following minimum lateral seismic force,

$$V_b = K_{D\max} D_D \tag{12}$$

If other displacements rather than D_D generate larger forces, then those forces should be used in design rather than the force obtained from Equation (12).
The structure above the isolation plane should withstand a minimum shear force, V_s, as if it was fixed base where:

$$V_s = \frac{K_{D\max} D_D}{R_1} \tag{13}$$

In above equations K_{Dmax} is the maximum effective stiffness of the isolation system at the design displacement (DBE) in the horizontal direction and R_I is a reduction factor analogous to the R factor that would have been used for the superstructure if it was not isolated. IBC-2000 defines R_I as

$$1.0 \le R_1 = \frac{3}{8} R \le 2.0 \tag{14}$$

If dynamic analysis is performed, it is possible to have design displacements and design forces that are less than those given by Equations (12) and (13). In such cases, the total design displacement, D_{TD}, for the isolation system can be reduced to not less than 90% of that given by the static formula, and the total maximum displacement, D_{TM}, can be reduced to not less than 80% of the static formula result. Furthermore, the code permits a further reduction by replacing D_D and D_M in the static formulas by D'_D and D'_M, where

$$D'_D = \frac{D_D}{\sqrt{1 + \left(T/T_D \right)^2}} \tag{15}$$

$$D'_M = \frac{D_M}{\sqrt{1 + \left(T/T_M \right)^2}} \tag{16}$$

In all cases the value of V_s should not be less than

1. The seismic force required by the code provisions for a fixed-base structure;

2. The base shears corresponding to the factored design wind load.
3. One and half times the lateral force required to fully activate the isolation system, i.e., the yield load of a lead-plug rubber bearing or slip threshold of a sliding bearing system.

3.2.5 Vertical Distribution of Design Force

To conservatively consider participation of higher modes in response, the vertical distribution of the force on the superstructure of an isolated building is similar to that prescribed for fixed-base construction.

This is so, although the seismic isolation theory suggests a uniform distribution of forces over the height of the superstructure. Therefore, the lateral force at level x, denoted by F_x is computed from the base shear, V_S, by

$$F_x = V_S \frac{h_x w_x}{\sum_{i=1}^{N} w_i h_i} \tag{17}$$

where w_x and w_i are the weights at level i or x and h_x and h_i are the respective heights of structure above isolation level.

3.2.6 Drift Limitations

The maximum interstorey drift (relative displacement of adjacent floors) permitted by the IBC-2000 is a function of method of analysis in that more drift is permitted when more sophisticated analyses are performed.

- Static Analysis

The drift at any level x is calculated from Equation (18) and should not exceed $0.015h_{sx}$ (h_{sx} is the story height below level x).

$$\delta_x = \frac{R_I \delta_{se}}{I_E} \tag{18}$$

where δ_{se} is the drift determined by an elastic analysis and I_E is the occupancy importance factor for the building.

- Response Spectrum Analysis

The drift at any level x calculated from response spectrum analysis should not exceed $0.015h_{sx}$.

- Time-History Analysis

The drift at any level x calculated from a time-history analysis considering the nonlinear behavior of the isolators should not exceed $0.020h_{sx}$.
The code has an additional paragraph stating that this drift should be calculated using Equation (18).
However, the relevance of such a provision to nonlinear time-history analysis is not clear. P-Δ effects must be considered whenever the interstorey drift ration exceeds $0.010/R_I$.

4. R.C.C BUILDING – BASE FIXED

4.1 INTRODUCTION

All real physical structures, when subjected to loads or displacements, behave dynamically. The additional inertia forces, from Newton's second law, are equal to the mass times the acceleration. If the loads or displacements are applied very slowly then the inertia forces can be neglected and a static load analysis can be justified. Hence, dynamic analysis is a simple extension of static analysis.

All real structures potentially have an infinite number of displacements. Therefore, the most critical phase of a structural analysis is to create a computer model, with a finite number of mass less members and a finite number of joint displacements that will simulate the behavior of the real structure. The mass of a structural system, which can be accurately estimated, is lumped at the nodes. Also, for linear elastic structures the stiffness properties of the members can be approximated with a high degree of confidence. However, the dynamic loading, energy dissipation properties and boundary (foundation) conditions for many structures are difficult to estimate.

To reduce the errors in calculations it is necessary to conduct many different dynamic analyses using different computer models, loading and boundary conditions. Because of the large number of computer runs required for a typical dynamic analysis, it is very important that accurate and numerically efficient methods be used within computer programs. So, proper knowledge of the dynamic analysis is very much essential.

Some computer program like DRAIN-2DX is available which is able to perform base isolation with dynamic analysis. The other software available to perform base isolation with dynamic analysis is ETABS & SAP2000. Out of these software two software's were available at departmental computer laboratory namely ETABS version 8.11 and SAP 2000 v 8.08.

Extended Three Dimensional Buildings Systems (ETABS) and Structural Analysis Program (SAP) are the products of Computer and Structures, Inc. These are the commercial windows finite element program that works with complex geometry and has inbuilt feature of provision of non-linear and linear bearings in the form of link element. With these built-in features it can model LRB, HDR and FPS bearings with different properties. SAP 2000 is general software, which has been used to analyze the fixed base RCC building and to model bearings in the isolated base RCC building.

4.2 GEOMETRY OF BUILDING

For the purpose of analysis of fixed base building an existing RCC building located in Ahmedabad was selected. The building is a moment resisting frame structure with Basement + GF + 4 storeys. The plan dimensions of the building are 22.982 m x 16.04 m as shown in the architectural drawings in FIGURE 4.1 to 4.4. As shown in FIGURE 4.5 the total height of the building is 19.2 m with typical slab top to slab top height of 3 meters.

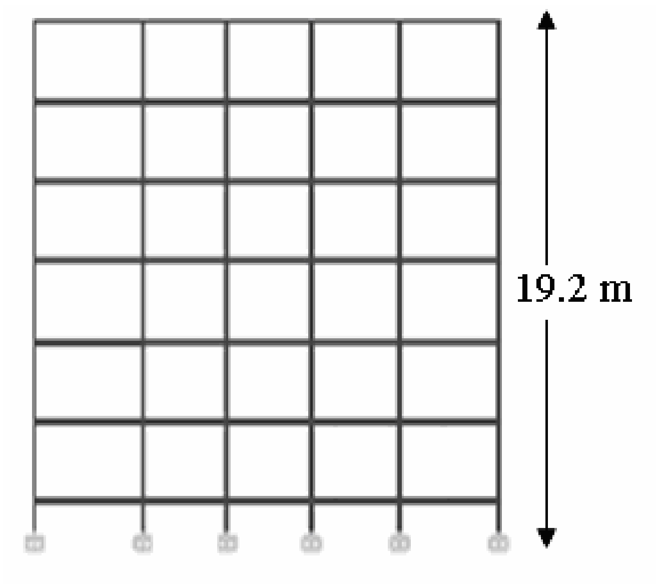


FIGURE 4.5 ELEVATION OF BUILDING

4.2.1 MATERIAL PROPERTIES

The selection of material properties is very important as the analysis results are very much governed by the properties used for the analysis. The properties of concrete and masonry were taken as used by the Structural Consultant. Material used for the beams and columns in the building were concrete with M20 grade & M25 grade. The building is having peripheral RC walls on all the levels. The basement is constructed with 230 mm thick RC wall while the walls above the basement 115 mm thick. Grade of steel used was f_y 250 and f_y 415 as reinforcing steel. The density of concrete, mass per unit volume, elastic modulus and Poisson's ratio used are given below in TABLE 4.1.

TABLE 4.1 MATERIAL PROPERTIES FOR FIXED BASE BUILDING

Description	Column	Beam	RC Strut	RC Walls
Density of Concrete (kN/m^3)	25	25	25	25
Mass per unit volume (kN/m^3)	2.4	2.4	2.4	2.4
Elastic Modulus (kN/m^2)	2.5E+7	2.2E+7	0.13E+7	2.2E+7
Poisson's ratio	0.20	0.20	0.20	0.20

Figure 4.6 shows the material property window for column in SAP2000 software. For the purpose of analysis all the materials were taken as isotropic with density of concrete taken as 25 kN/m^3.

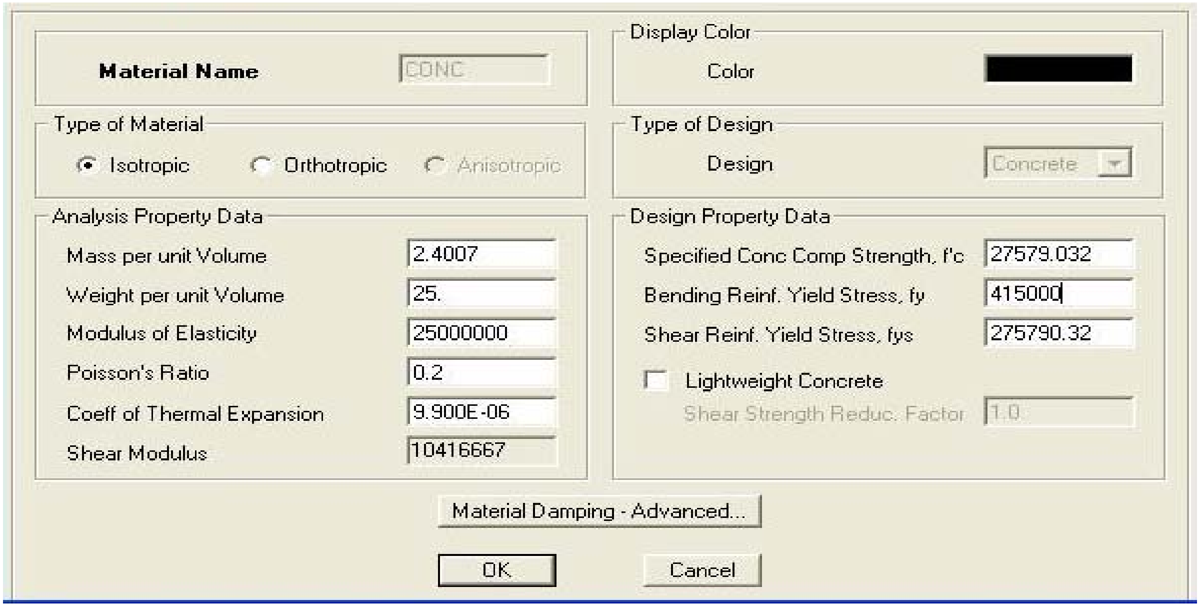


FIGURE 4.6 MATERIAL PROPERTIES WINDOW FOR COLUMN IN SAP2000

- **Boundary condition**

For the purpose of dynamic analysis all the nodes at the base are fixed against movement in x, y and z directions as shown in Figure 4.10.

- **Sectional properties**

The slab of the RCC building was 120 mm thick. The slab was modeled using thick shell element as shear deformations were also considered. Two types of beam sizes were used for the purpose of analysis. The beams were taken as rectangular section and the sizes selected are given below. Two types of columns sizes were used. Columns were also taken as rectangular in section. The sizes of columns are given below. FIGURE 4.7, 4.8 & 4.9 shows how the slabs, beams and columns sectional properties were entered in SAP2000.

Slab thickness = 0.12 m.

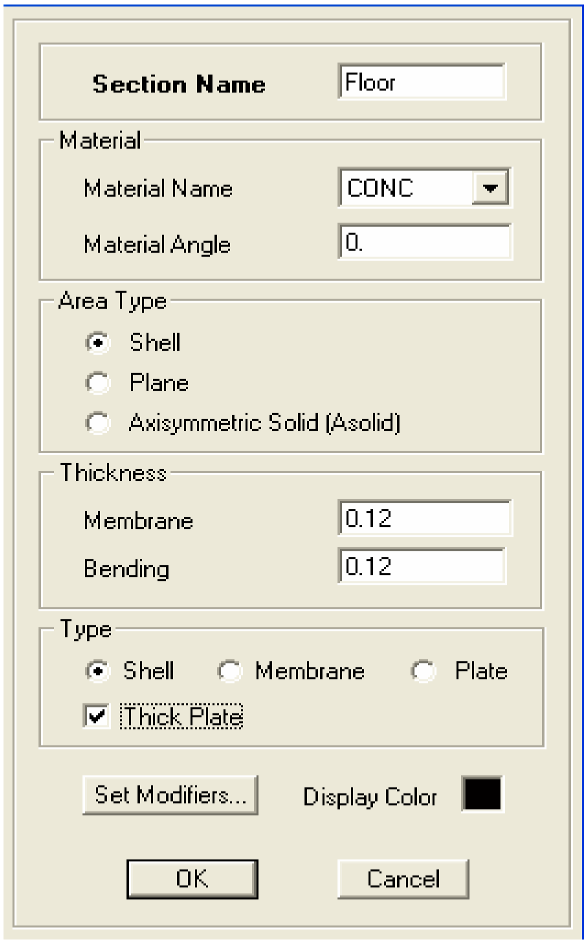


FIGURE 4.7 AREA PROPERTIES WINDOW IN SAP2000

Size of beams: -

1. 0.23 m x 0.45 m
2. 0.3 m x 0.6 m

Size of RCC walls (basement): -

1. Height = 3 m
2. Width = 0.23 m

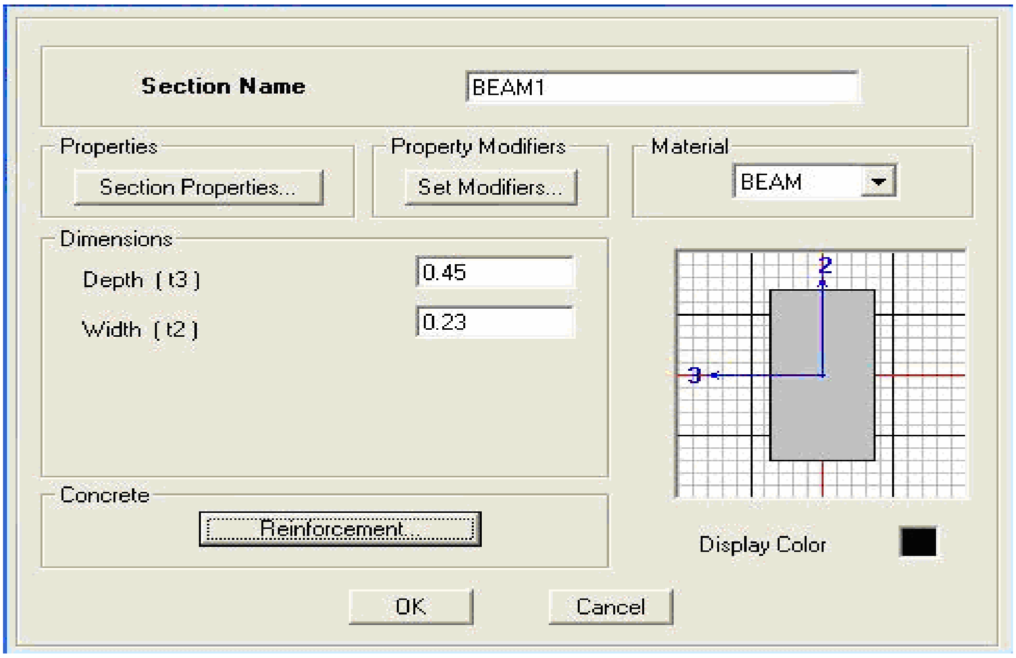


FIGURE 4.8 BEAM PROPERTIES WINDOW IN SAP2000

Size of columns:

1. 0.6 m x 0.3 m
2. 0.3 m x 0.6 m

L – Shape column: Outside vertical leg = 0.6 m, Outside horizontal leg = 0.6 m, Horizontal leg thickness = 0.3 m & Vertical leg thickness = 0.3 m

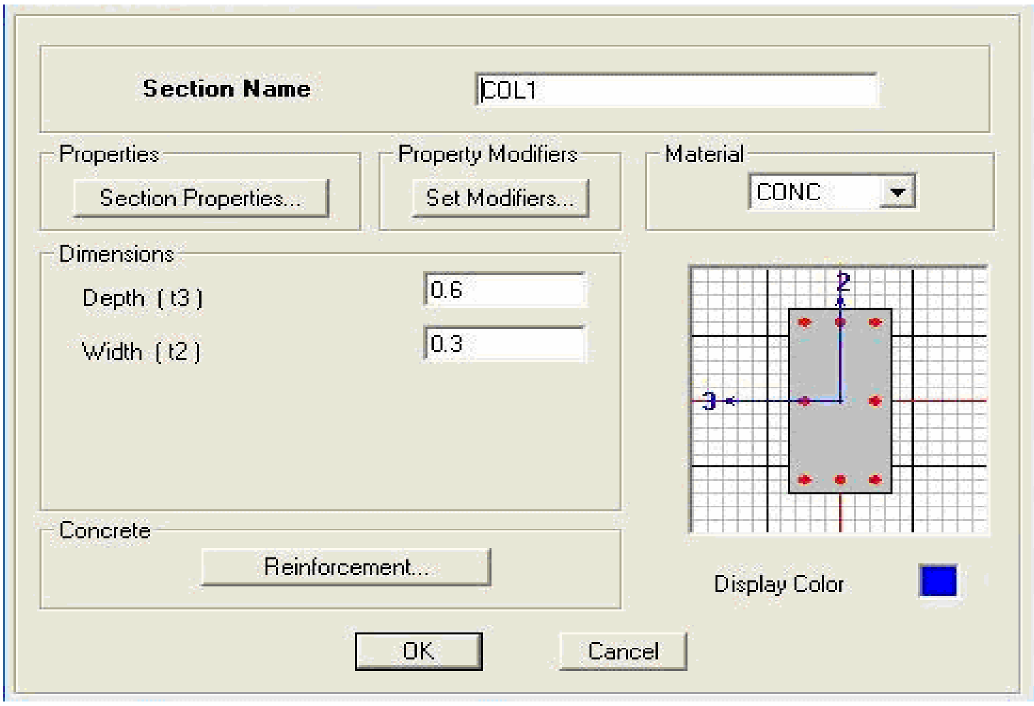


FIGURE 4.9 COLUMN PROPERTIES WINDOW IN SAP2000

- **Diaphragm Constraint**

All the slabs were assigned diaphragm constraints in lateral direction so as to have a rigid body action.

4.3 MODELING

Modeling of any structure in software is very crucial for performing any type of analysis using software. A small mistake in modeling can change the final analysis results drastically. Modeling of the structure in the software includes, creating grid system, adding the structural elements as per the drawing, defining the structural properties and assigning those structural properties to the respective structural elements.

The spacing of the grid lines are specified along global axes X, Y and Z. By default, software considers Z axis as vertical axis and X and Y are two horizontal axes. Also there are local axes 1, 2 and 3 for each structural element. Axis 1 is along the length of the element and axis 2 and axis 3 are the axis perpendicular to the axis 1.

The two options available to the software for defining grid systems are Uniform Grid Spacing and Custom Grid Spacing. Uniform grid spacing option specifies number of grid lines of uniform spacing in each direction while custom grid spacing allows defining non-uniformly spaced grid lines in two horizontal directions.

After defining grid system, frame/shell elements are to be defined. Two options are available for defining frame/shell elements data; draw frame/shell element, which draws a frame element between nodes & quick draw frame/shell element which draws frame elements on grid lines.

The structural properties of any structural elements are material properties & geometric properties. Material property defines the mass density, weight, modulus of elasticity strength of material, modulus of elasticity and poisons ratio. Geometric Property defines the cross sectional dimension and if the material property is concrete, it also defines the reinforcement details. Each of the properties is to be named and same is to be assigned to the respective structural elements.

Modeling of the building was carried out to generate a 3D model of a fixed base RCC building as shown in FIGURE 4.10. The basement of the building is constructed with 230 mm thick RCC periphery and inner walls which were modeled using shell area element. Walls above the basement were modeled as strut element with properties as shown in Table 4.1.

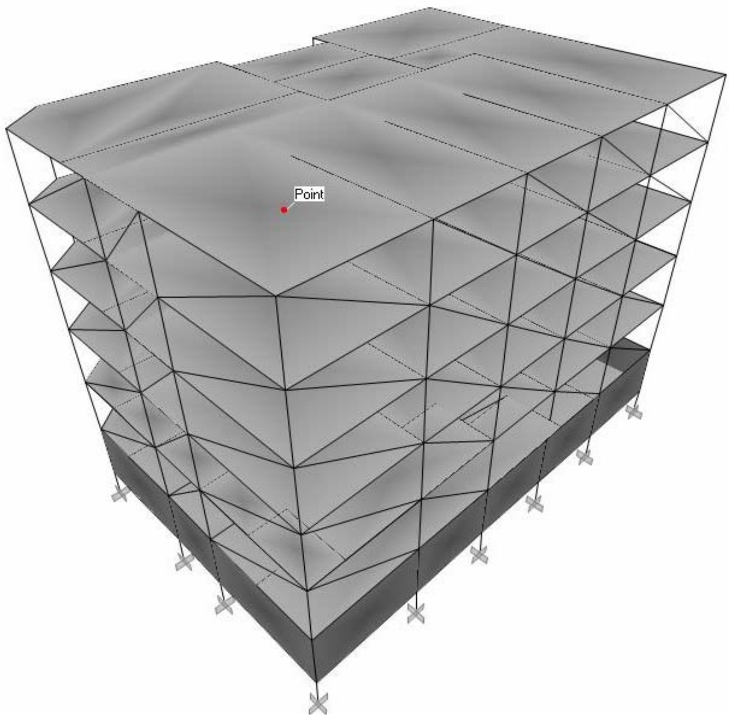


FIGURE 4.10 3-D MODEL OF RCC BUILDING IN SAP2000

4.3.1 Modeling of RC Infill Walls

The influence of the RC infill on the basic frame structural system is multiple. When a flexible RC frame structure is connected with rigid filler walls, the dynamic properties of the building change & short periods of vibrations result in increased seismic actions. In the elastic range & at small amplitudes of vibrations, lateral forces will be mainly carried by rigid infill, as the contribution of the flexible main system to the lateral resistance of the building at small displacements is not significant. If the filler walls are not designed to resist lateral forces at increased lateral deformations, they will be damaged.

The RCC infill affects the seismic behavior of the building in the following ways:

1. The stiffness of the building is increased, the fundamental time period is decreased and therefore the base shear due to seismic action is increased.
2. Part of the seismic action is carried by the infill, thus relieving the structural systems.

3. The ability of the building to dissipate the energy is substantially increased.

For lateral load resisting frame, the stiffness of infill wall and strength contribution has to be considered. Non-integral infill frame subjected to lateral load behaves like a diagonally braced frame. Hence, appropriately, infill wall can be replaced by an equivalent compression only strut in the analysis model.

- Modulus of Elasticity of Masonry

The modulus of elasticity of masonry is calculated from the formula given below:

$$E_m = 750 f_m \qquad [1]$$

where, f_m = Compressive strength of brickwork.

For calculation of the strut parameter here f_m has been taken as 1.65 N/mm^2.

So, modulus of elasticity, E_m=750×1.65 N/mm^2 =1237.5 N/mm^2

- Equivalent Width of Strut

The key to the equivalent diagonal strut approach lies in determination of effective width of the diagonal strut. For solid walls width of equivalent diagonal strut (w) can be taken as one third of the diagonal length (d) of the infill wall.

$$w = d/3 \qquad [2]$$

- Effects of Infill on the Analysis

The effects of the infills on the analysis must be considered together with the high degree of uncertainty related to their behavior. The effects of the infills on the analysis are as follows: -

i. The variability of their mechanical properties and therefore the low reliability in their strength and stiffness.
ii. Their wedging condition i.e. how tightly they are connected to the surrounding frame.
iii. The potential modification of the integrity during the use of the building

iv. The non- uniform degree of their damage during earth quake.

Thus modeling of infill wall in the analysis is very important as it will change the response of the building. There are two ways to model infill walls in the structure.

1. By equivalent strut approach
2. By Finite element modeling, assigning them as shell element, with only corner nodes connected to the frame system.

In SAP2000 the infill walls were modeled as a strut element. The dimensions of the strut were calculated using the criteria given above. TABLE 4.2 gives the excel spreadsheet calculations for calculating the dimensions of the strut. After calculating the width of the strut and thickness, they were model in the building using frame element with properties as mentioned in TABLE4.1.

TABLE 4.2 CALCULATIONS OF STRUT DIMENSIONS

Length of wall	Height of wall	Diagonal length	Width of Strut	Thickness of Strut
5.37	3.00	6.15	2.05	0.12
4.17	3.00	5.14	1.71	0.12
4.36	3.00	5.30	1.77	0.12
4.90	3.00	5.75	1.92	0.12
3.69	3.00	4.76	1.59	0.12
8.10	3.00	8.64	2.88	0.12
5.98	3.00	6.69	2.23	0.12
5.03	3.00	5.86	1.95	0.12
3.05	3.00	4.28	1.43	0.12
5.62	3.00	6.37	2.12	0.12
5.34	3.00	6.12	2.04	0.12
14.88	3.00	15.18	5.06	0.12
1.16	3.00	3.22	1.07	0.12
3.20	3.00	4.39	1.46	0.12
9.54	3.00	10.00	3.33	0.12
3.16	3.00	4.36	1.45	0.12
3.85	3.00	4.88	1.63	0.12
7.01	3.00	7.62	2.54	0.12

Modeling strut in SAP2000 can be done in different ways.

1. Releasing the moments & shears and only allowing axial force for frame element.
2. Using link element and model it as compression and tension member.

For the purpose of analysis we have applied moment releases in one direction to struts and modeling it as a frame element. FIGURE 4.11 shows a shear and moment releases applied at the start node of the strut member in frame element.

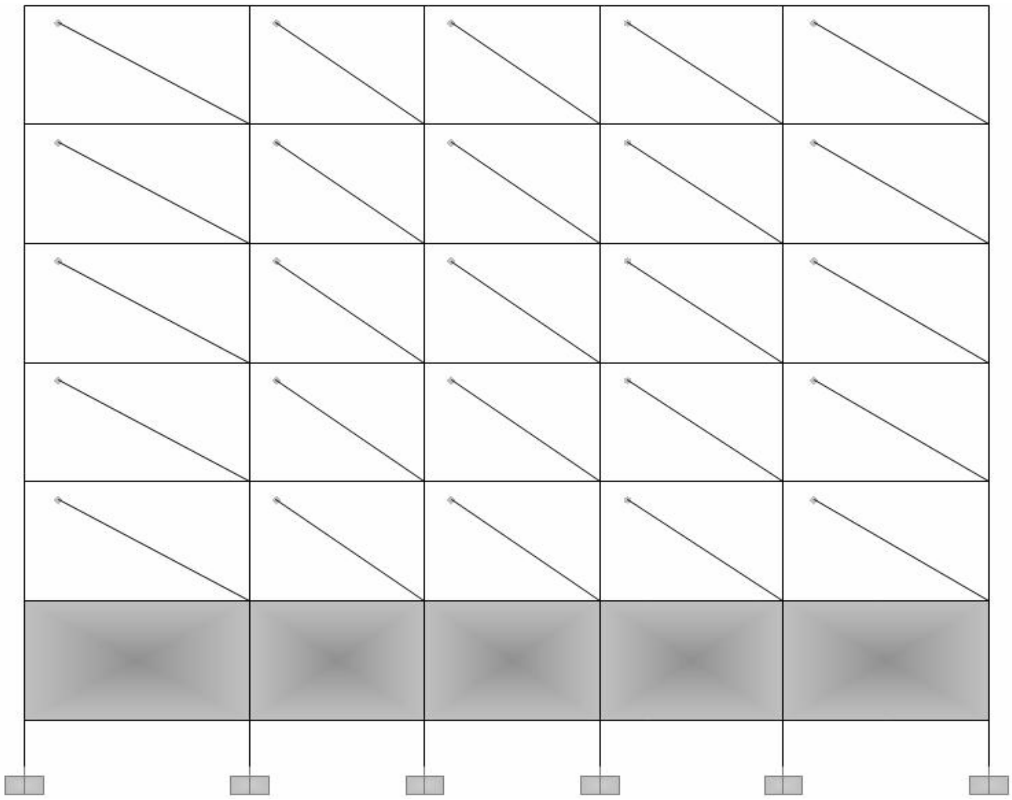


FIGURE 4.11 SHEAR & MOMENT RELEASES APPLIED TO THE STRUT

4.4 ANALYSIS IN SAP2000

Two types of analysis were carried out in SAP2000 for the building.

1. Static Analysis
2. Dynamic Analysis (Response Spectrum Analysis)

4.4.1 Static Analysis

The software incorporates the dead load automatically while live load is to be manually applied at each floor as per IS 875-Part I. For the office building used, live load of 2 kN/m^2 was used which was applied at all the floors as area load.

The other load cases required to be define are Lateral loads in two different horizontal (X and Y) directions. It is achieved by applying maximum load at the top of the structure which subsequently reduces to zero at the bottom. Static Analysis was carried out for Dead load and Live Load cases.

- **Loads Considered**
  1. DL
  2. LL

4.4.2 Dynamic Analysis

For earthquake analysis, Response Spectrum Cases is to be defined as the software doesn't supports IS 1893-2002. The response spectrum given in IS 1893-2002 for 5% damping is to be defined and same is to be used for performing Response Spectrum Analysis. The modal combination options available with the software are Complete Quadratic Combination (CQC), Square Root of the Sum of the Squares (SRSS), Absolute Method (ABS) and General Modal Combination (GMC) method. Modal combination produces a single, positive result for each direction of acceleration. These directional values are combined to produce a single, positive result. There are two options available for the directional combination: SRSS and ABS.

Dynamic analysis includes static analysis also. While performing Dynamic analysis, the analysis window provides some important information like number of modes found, frequency of each mode, time period of each mode and modal participation factor. Once the analysis is performed successfully, the results like deformations, shear forces, bending moments of each element can be displayed or listed for each load cases and load combinations cases defined.

Response Spectrum Dynamic Analysis was carried out for the building using design response spectrum of IS 1893 Part I for medium soil conditions and damping of 5 %. The building is situated in Ahmedabad and hence zone factor, z was taken as 0.16, Importance factor of 1 as it is a office building, Response reduction factor R = 3 as it is an ordinary moment resisting frame and Sa/g for 5 % damping from IS 1893-2002. FIGURE 4.12 shows the response spectrum function definition window in SAP2000. As SAP2000 doesn't incorporate the response spectrum curve of IS 1893-2002 Part 1, the data was entered manually as a user defined function.

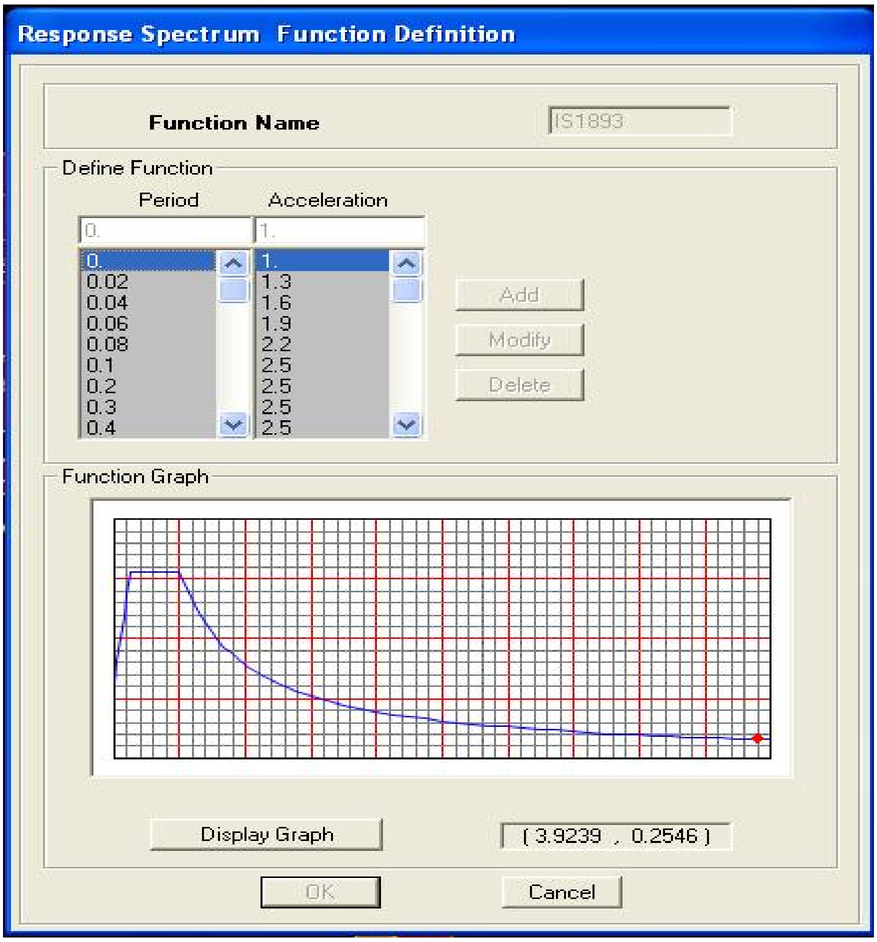


FIGURE 4.12 RESPONSE SPECTRUM FUNCTION DEFINITON IN SAP2000

- **Loads Considered**

  1. Earthquake Load

- **Load Combinations**

The following load combinations as specified by IS1893-2002 Part-1 were used for analyzing the building.

1. 1.5DL+1.5LL
2. 1.5DL+1.5EQ+X
3. 1.5DL+1.5EQ-X
4. 1.5DL+1.5EQ+Z
5. 1.5DL+1.5EQ-Z
6. 1.2DL+1.2LL+1.2EQ+X
7. 1.2DL+1.2LL+1.2EQ-X
8. 1.2DL+1.2LL+1.2EQ+Z

9. 1.2DL+1.2LL+1.2EQ-Z
10. 0.9DL+1.5EQ+X
11. 0.9DL+1.5EQ-X
12. 0.9DL+1.5EQ+Z
13. 0.9DL+1.5EQ-Z

4.5 OUTPUT OF ANALYSIS

After carrying out the dynamic response spectrum analysis results were obtained and they are explained in detail in chapter 7. For the purpose of design of bearings preliminary results are presented below. Since the bearings are generally designed to carry 100 % gravity loads, for the purpose of initial design axial forces in the form of service load is required.

FIGURE 4.13 shows the frame numbering in the fixed base RCC building.

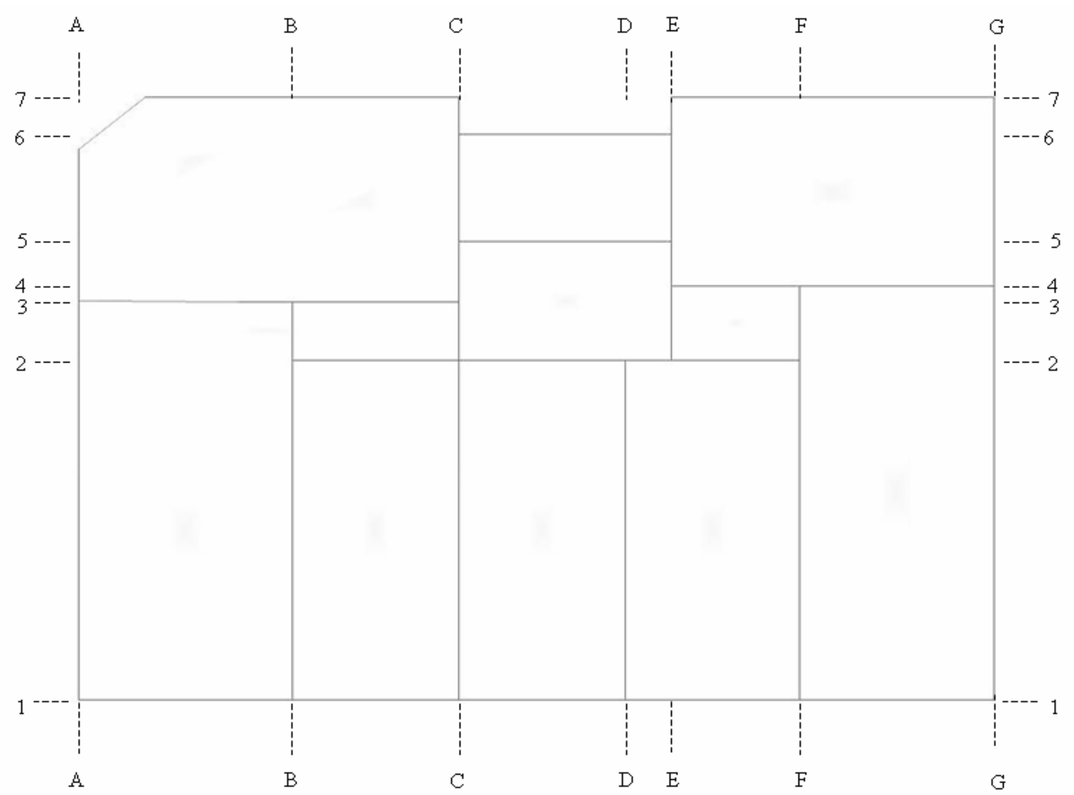


FIGURE 4.13 FRAME SECTIONS FOR FIXED BASE RCC BUILDING

FIGURE 4.14 and 4.15 shows the maximum axial force obtained for the service load condition in frame 1-1 and frame 7-7 of the building. Maximum axial force was obtained under column number G 7 in frame 7-7.

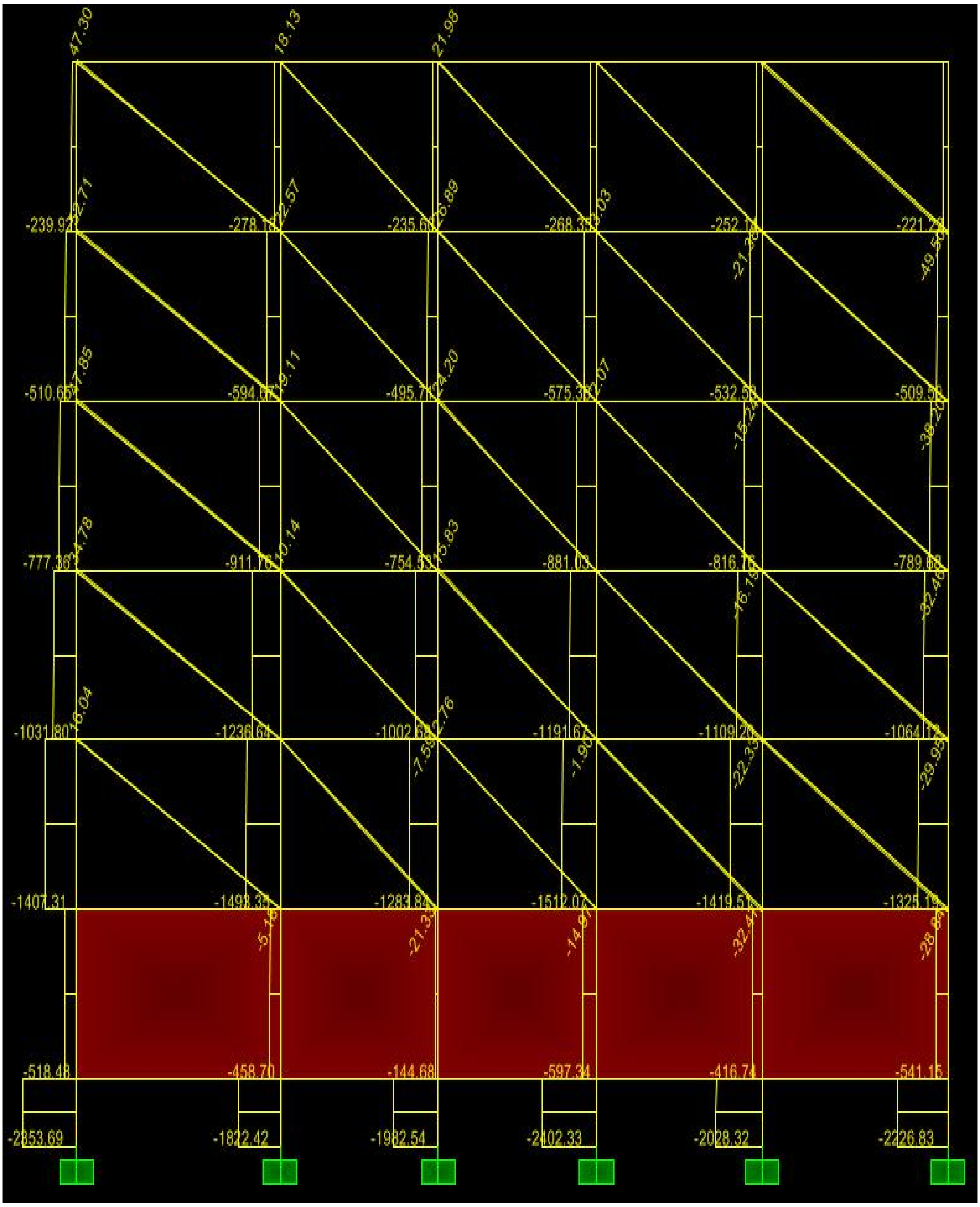


FIGURE 4.14 MAXIMUM AXIAL FORCES FOR FRAME 1-1 FOR SERVICE LOAD

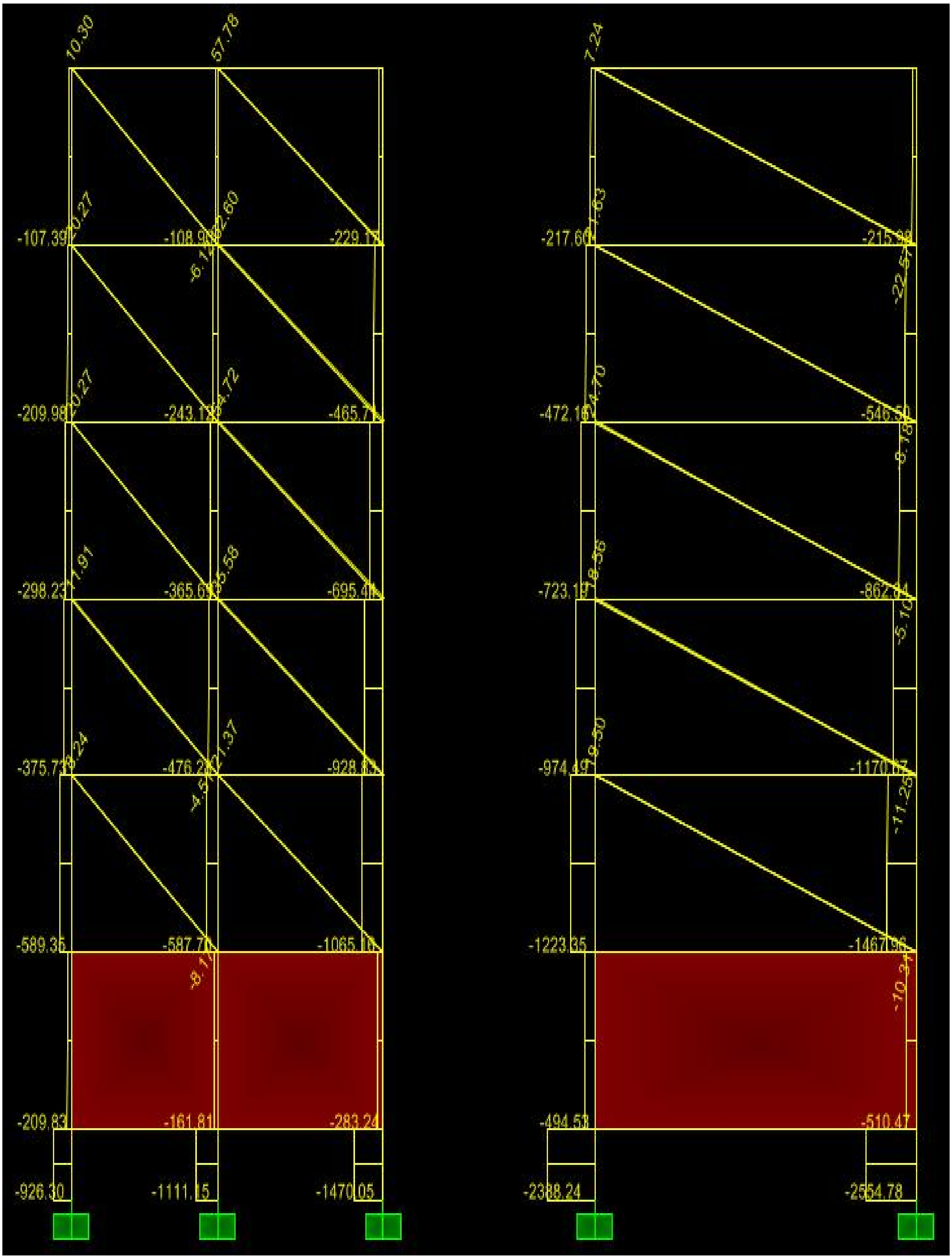
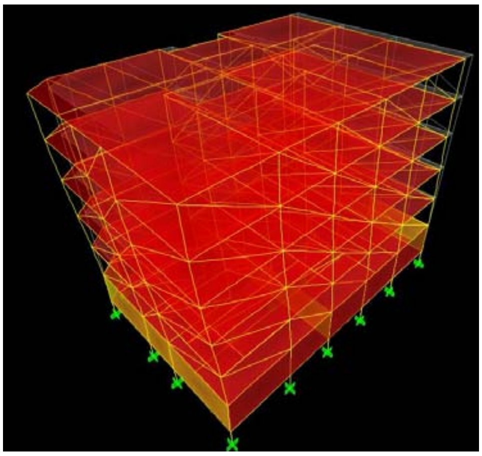
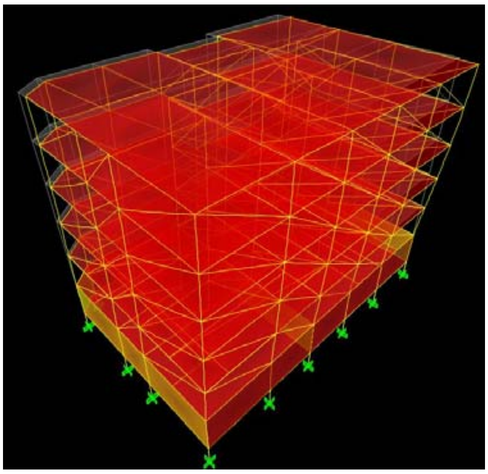
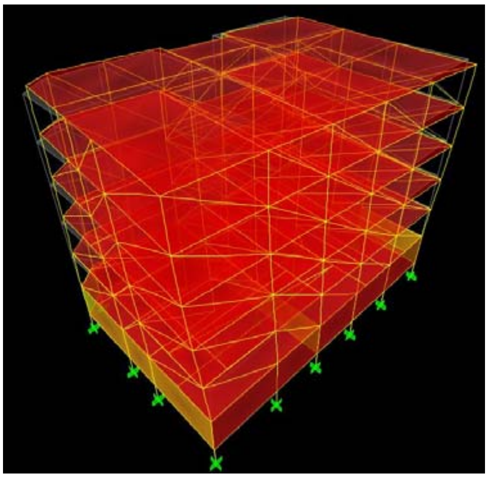


FIGURE 4.15 MAXIMUM AXIAL FORCES FOR FRAME 7-7 FOR SERVICE LOAD

TABLE 4.3 gives the output of fixed base building in the form of modal time period and mode shape for the first three modes. Mode 1 is the first fundamental mode with a period of 0.42 sec in X direction

TABLE 4.3 TIME PERIOD AND MODE SHAPES OF BUILDING FROM SAP2000

Mode No.	Time Period [seconds]	Mode Shape	Mode of vibration
1	0.42		X-direction
2	0.40		Y-direction
3	0.34		Torsion

5. DESIGN OF BEARINGS

As design is considered on basis of IBC 2000 following input is required.

Location of building: Ahmedabad

Site Class: B (As site is far away from active faults)

Response Reduction Factor, R = 6 (IBC 2000, section 1623.2.5.2)

D.L = Self weight of building (Assumed initially)

L.L = 2 kN/m^2

Storey height = 3 ^{m}

As isolated building is first designed for gravity loads mainly account of dead load and live load input is made in the from of axial load and total weight of the building.

P_{DL+LL}= Max. Service Load on column = 2600 kN (Fixed base building)

W_T = Total weight of building = 30238.5 kN (Fixed base building)

For base isolation R_I i.e. Response Reduction Factor for base isolated condition is modified as,

$$1.0 \le R_I = 3/8\ R \le 2.0$$

$$= 3/8 \times 6 = 2.25 > 2 \text{ (which is not possible)}$$

So, R_I = 2.0 (for base isolated building)

Preliminary Design Targets

As base isolation requirements suggest that the period of building has to be lengthened to at least three times that of fixed base building, therefore the target period for all the types of bearing is taken as 2.5 seconds.

With these input, it is possible to design different types of bearing for the building undertaken.

5.1 DESIGN OF LEAD RUBBER BEARING

Design Data

i) Target period, T_D = 2.5 sec;
ii) LRB has a maximum shear strain = 50 % i.e. γ_{max} = 50 %;
iii) For effective damping ratio, ξ_{eff} = 10 %, B_D i.e. Damping coefficient = 1.2 [from Table 1623.2.2.1 – IBC 2000] and

iv) Seismic coefficient, S_D = 0.4 considering site condition of isolated building with long periods.

5.1.1 Analysis

Effective horizontal stiffness K_{eff} of the isolator is,

$$k_{eff} = \left(\frac{W}{g}\right)\left(\frac{2\Pi}{T_d}\right)^2 = \left(\frac{2600}{9.81}\right)\left(\frac{2\Pi}{2.5}\right)^2 = 1674.11 \text{ kN/m}$$

$$= 1.67 \text{ MN/m}$$

Where, W = P_{DL+LL}

From equation 16-79 of IBC 2000, D_D = Design displacement

$$= \left(\frac{g}{4\Pi^2}\right)\left(\frac{S_D \times T_D}{B_D}\right)$$

$$= \left(\frac{9.81}{4\Pi^2}\right)\left(\frac{0.4 \times 2.5}{1.2}\right)$$

$$= 0.21 \text{ m}$$

So, D_D = 0.21 m = 210 mm

The short term yield force Q_d is,

$$Q_d = \frac{W_d}{4D_D} = \frac{\Pi}{2} k_{eff}\, \xi_{eff}\, D_D$$

$$= \frac{\Pi}{2}(1674.11 \times 0.10 \times 0.21)$$

$$= 55.17 \text{ kN}$$

The post yield horizontal stiffness k_d is,

$$k_d = k_{eff} - \frac{Q_d}{D_D} = 1674.11 - \frac{55.17}{0.21} = 1411.39 \text{ kN/m}$$

5.1.2 Design of bearing

- Design of Lead Core

Assume yield strength of Lead core to be f_{py} = 8.82 MN/m^2

$\therefore$ Required Lead area = $A_p = \dfrac{Q_d}{f_{py}} = \dfrac{55.17}{8.82 \times 10^3} = 6.26 \times 10^{-3}\ m^2 = 62.55 \text{ cm}^2$

$$A_p = \frac{\Pi}{4} d^2$$

$$\therefore d^2 = \frac{62.55 \times 4}{\Pi}$$

$\therefore d = 9$ cm

$\therefore$ Use diameter = d_p = 9 cm

- Total height of rubber layer: -

Total rubber height, $t_r = \left(\frac{D_D}{\gamma_{max}}\right) = \left(\frac{0.21}{0.5}\right)$ = 0.42 m

- Rubber Properties used

Rubber hardness = IRHD 70

Young's modulus = E = 735 N/cm^2

Shear modulus = G = 173 N/cm^2

Modified factor = k = 0.53

Elongation at break = ϵ_b = 500 %

- Design the area and dimensions for rubber layer

Select Shape factor S

$$\mathrm{E} \times \left(\frac{1 + 2kS^2}{G}\right) \geq 400$$

$$\therefore 735 \times \left(\frac{1 + 2 \times 0.53 \times S^2}{173}\right) \geq 400$$

$$\therefore 1 + 2 \times 0.53 \times S^2 \geq 94.15$$

$$\therefore 1.06 S^2 \geq 93.15$$

$$\therefore S^2 \geq 87.88$$

$$\therefore S \geq 9.37$$

Use, S = 10

$$E_c = E\left(1 + 2kS^2\right)$$

$$= 735\left(1 + \left(2 \times 0.53 \times 10^2\right)\right)$$

$= 78645$ N/cm^2

$= 786.45$ MN/m^2

- Determine the effective area A_o for the bearing based on allowable axial stress σ_c under the vertical load case P_{DL+LL}

$$\sigma_c = \frac{P_{DL+LL}}{A_o} \le 7.84 \text{ MN/m}^2$$

$$\therefore A_0 > \frac{2.6}{7.84} \text{ m}^2$$

$$\therefore A_0 > 0.33 \text{ m}^2$$

- Determine the effective area A_1 for the bearing from the shear strain condition under the vertical load case P_{DL+LL}

$$6 \times S \times \frac{P_{DL+LL}}{E_c \times A_1} \le \frac{\varepsilon_b}{3}$$

$$\therefore 6 \times 10 \times \frac{2.6}{786.45 \times A_1} \le \frac{500\%}{3}$$

$$\therefore A_1 > 0.12 \text{ m}^2$$

- Determine the Elastic stiffness k_r of the bearing

$$k_d = k_r \left(1 + 12 \frac{A_p}{A_o}\right)$$

$$1409.7 = k_r \left(1 + 12 \frac{0.00626}{0.33}\right)$$

$$k_r = 1149.52 \quad \text{kN/m}$$

- Determine the effective area A_{sf} of individual rubber layers based on shear failure of bearing

$$G = \frac{k_r \times t_r}{A_{sf}}$$

$$\therefore A_{sf} = \frac{k_r \times t_r}{G} = \frac{1149.52 \times 0.42}{1730} = 0.28 \text{ m}^2$$

Assume, Length of bearing = L = 0.25 m

Breadth of bearing = B = 0.55 m

$$\therefore A_2 = L(B - D_D) = 0.25 \times (0.55 - 0.21) = 0.09 \quad \text{m}^2$$

- Design cross-sectional area for the bearing

A = max (A_0, A_1, A_2)

= max (0.33, 0.12, 0.09)

= 0.33 m^2

- Single layer thickness, t & number of layers, N for a circular bearing

$$S = \frac{L \times B}{2(L+B) \times t}$$

$$\therefore 10 = \frac{0.25 \times 0.55}{2(0.25+0.55) \times t}$$

$\therefore t = 8.59 \times 10^{-3}$ m

$\therefore t = 0.86$ cm

$t_r = N \times t$

$\therefore 0.42 = N \times 0.0086$

$\therefore$ N = 50

- Determine the steel plate thickness t_s

$$t_s \geq \left(\frac{2(t_i + t_{i+1}) \times P_{DL+LL}}{A_{re} \times F_s} \right) \geq 2 \text{ mm}$$

$$t_s \geq \left(\frac{2(0.0086 + 0.0086) \times 2.6}{0.09 \times (0.6 \times 274.4)} \right) = 6.04 \times 10^{-3} \ m = 6.39 \ mm$$

$\therefore$ Use, t_s = 6.39 mm

Where, for A36 steel

$F_s = 0.6\ f_y = 0.6 \times 274.4$ MN/m^2 & A_{re} = 0.09 m^2.

- Total height h of the bearing

Assume both the top and bottom cover plates as 2.5 cm thick.

$\therefore$ Total height of bearing is, h = t_r + N $\times$ ts + 2 $\times$ 2.5

= 42 cm + 50 $\times$ 6.39 mm + 2 $\times$ 2.5 cm

= 78.93 cm

5.1.3 Check for shear strain and stability conditions

- Check for shear strain under vertical load P_{DL+LL}

Shear strain under vertical load = $\gamma_{c,\,DL+LL}$ = $6 \times S \times \dfrac{P_{DL+LL}}{E_c \times A}$

$$= 6 \times 10 \times \frac{2.6}{786.45 \times 0.33}$$

$$= 0.6 \le \frac{\varepsilon_b}{3} = \frac{500\%}{3} = 1.667$$

$\therefore$ OK

- Stability check

$$\sigma_c = \frac{P}{A} = \frac{2600}{0.33} = 7840 \text{ kN/ m}^2$$

$$\le \sigma_c = \frac{G \times S \times L}{2.5 \times t_r} = \frac{(173 \times 10) \times 10 \times 0.55}{2.5 \times 0.42} = 9061.90 \text{ kN/ m}^2$$

$\therefore$ OK

- Check on diameter of Lead core

$$1.25 \le \frac{H_p}{d_p} = \frac{42}{9} = 4.667 < 5$$

$\therefore$ Use Diameter of Lead core = 10 cm

- Check on Stability under Earthquake Load

Shear Strain condition including the Earthquake Effect

$P_{DL+LL+EQ}$ = 2225.01 kN = 2.22 MN

Strain due to compression, γ_{sc} = $\dfrac{6 \times S \times P}{A_{re} \times E_c} = \dfrac{6 \times 10 \times 2.22}{0.28 \times 786.45} = 0.606$

Strain due to Earthquake, γ_{eq} = $\dfrac{D_D}{t_r} = \dfrac{0.21}{0.42} = 0.5$

$$\therefore \vartheta = \frac{12 \times D_D \times e}{b^2 + d^2} = \frac{12 \times 0.21 \times (0.05 \times 22.982)}{\left((16.04)^2 + (22.982)^2\right)} = 0.0036$$

Strain due to Rotation, γ_{sr} = $\dfrac{B^2 \times \vartheta}{2 \times t \times t_r} = \dfrac{55^2 \times 0.0036}{2 \times 0.86 \times 42} = 0.154$

$\therefore \gamma_{sc} + \gamma_{eq} + \gamma_{sr} = 1.26$

$< 0.75\varepsilon_b = 0.75 \times 5 = 3.75$

$\therefore OK.$

- Check on Roll-out under Earthquake Load

$$\delta_{roll-out} = \frac{1}{2} \times \frac{P \times L - Q_d \times h}{P + k_d \times h}$$

$$= \frac{1}{2} \times \frac{2225.01 \times 0.7 - 55.17 \times 0.789}{2225.01 + (1409.7 \times 0.789)}$$

$= 226.79$ mm

$> D_D = 210$ mm

$\therefore$ *Safe*

5.1.4 Design Results - Dimensions of Lead Rubber Bearing

The design result for Lead rubber bearings is as shown here in a tabular form in TABLE 5.1.

TABLE 5.1 DESIGN RESULTS FOR LEAD RUBBER BEARING (mm)

Length of bearing, L	250
Width of bearing, B	550
Diameter of Lead core	100
Total height of bearing, h	789
No. of rubber layers, N	50
Thickness of individual rubber layers, t	8.6
Number of steel plates, N_s	50
Thickness of individual steel plates, t_s	6.4
Thickness of top and bottom cover plates	25

A figure consisting of above mentioned properties is shown in FIGURE 5.1.

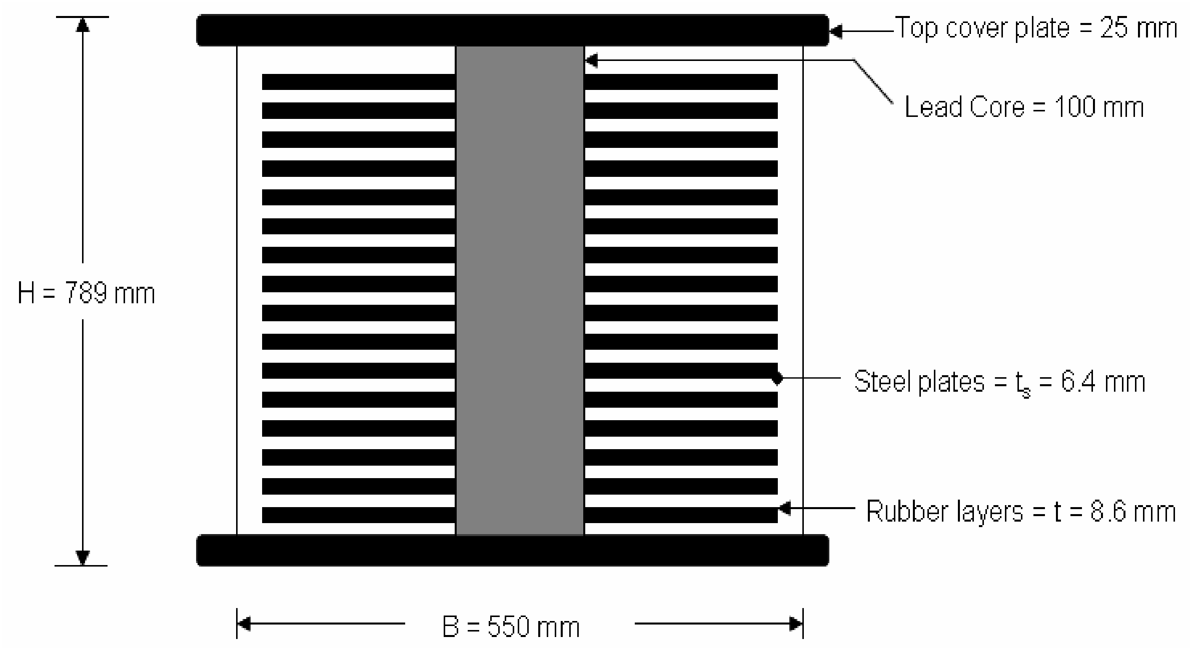


FIGURE 5.1 DIMENSIONS OF LRB

5.2 DESIGN OF HIGH DAMPING RUBBER BEARING

Design Data

i) Target period, T_D = 2.5 sec;

ii) HDR has a maximum shear strain = 150 % i.e. γ_{max} = 150 %;

iii) For effective damping ratio, ξ_{eff} = 20 %, B_D i.e. Damping coefficient = 1.5 [from Table 1623.2.2.1 – IBC 2000] and

iv) Seismic coefficient, S_D = 0.4 considering site condition of isolated building with long periods.

5.2.1 Analysis

Effective horizontal stiffness K_{eff} of the isolator is,

$$k_{eff} = \left(\frac{W}{g}\right)\left(\frac{2\Pi}{T_d}\right)^2 = \left(\frac{2600}{9.81}\right)\left(\frac{2\Pi}{2.5}\right)^2 = 1674.11 \text{ kN/m}$$

$$= 1.67 \text{ MN/m}$$

Where, W = P_{DL+LL}

From equation 16-79 of IBC 2000, D_D = Design displacement

$$= \left(\frac{g}{4\Pi^2}\right)\left(\frac{S_D \times T_D}{B_D}\right)$$

$$= \left(\frac{9.81}{4\Pi^2}\right)\left(\frac{0.4 \times 2.5}{1.5}\right)$$

= 0.17 ^{m}

So, D_D = 0.17 ^{m} = 170 mm

5.2.2 Design of bearing

- Calculation of Isolator size: -

Total rubber height, $t_r = \left(\frac{D_D}{\gamma_{max}}\right)$ = $\left(\frac{0.17}{1.5}\right)$ = 0.11 ^{m}

Therefore, use t_r = 0. 12 ^{m}

- Rubber Properties used: -

Rubber hardness = IRHD 60

Young's modulus = E = 445 N/cm^2

Shear modulus = G = 106 N/cm^2

Modified factor = k = 0.57

Elongation at break = ϵ_b = 500 %

- Calculation of Area A & thickness t of individual rubber layers

Selection of Shape factor S

$$\mathrm{E}\times\left(\frac{1+2kS^2}{G}\right)\geq 400$$

$$\therefore 445\times\left(\frac{1+2\times 0.57\times S^2}{106}\right)\geq 400$$

$$\therefore 1+2\times 0.57\times S^2 \geq 95.28$$

$$\therefore 1.14S^2 \geq 94.28$$

$$\therefore S^2 \geq 82.70$$

$$\therefore S \geq 9.09$$

Use, S = 10

$$E_c = E\left(1+2kS^2\right)$$

$$= 445\left(1+\left(2\times 0.57\times 10^2\right)\right)$$

$= 51175$ N/cm^2

$= 511.75$ MN/m^2

- Effective area A_o for the bearing based on allowable axial stress σ_c for the vertical load case

$$\sigma_c = \frac{P_{DL+LL}}{A_o} \le 7.84 \text{ MN/m}^2$$

$$\therefore A_0 > \frac{2.6}{7.84} \text{ m}^2$$

$$\therefore A_0 > 0.33 \text{ m}^2$$

- Determine the effective area A_1 for the bearing from the shear strain condition under the vertical load case P_{DL+LL}

$$6 \times S \times \frac{P_{DL+LL}}{E_c \times A_1} \le \frac{\varepsilon_b}{3}$$

$$6 \times 10 \times \frac{2.6}{511.75 \times A_1} \le \frac{500\%}{3}$$

$$\therefore A_1 > 0.18 \text{ m}^2$$

- Obtain the minimum area A_{sf} for shear failure of bearing

$$G = \frac{k_{eff} \times t_r}{A_{sf}}$$

$$\therefore A_{sf} = \frac{k_{eff} \times t_r}{G} = \frac{1.67 \times 0.12}{1.06} = 0.19 \text{ m}^2$$

Assume, Length of bearing = L = 0.25 m

Breadth of bearing = B = 0.55 m

$$\therefore A_2 = L(B - D_D) = 0.25 \times (0.55 - 0.17) = 0.10 \text{ m}^2$$

- Design cross-sectional area for the bearing

A = max (A_0, A_1, A_2)

= max (0.33, 0.18, 0.10)

= 0.33 m^2

- Single layer thickness, t & number of layers, N for a circular bearing

$$S = \frac{L \times B}{2(L + B) \times t}$$

$$\therefore 10 = \frac{0.25 \times 0.55}{2(0.25 + 0.55) \times t}$$

$\therefore t = 8.59 \times 10^{-3}$ m

$\therefore t = 0.86$ cm

$t_r = N \times t$

$\therefore 0.12 = N \times 0.0086$

$\therefore$ N = 14

- Determine the steel plate thickness t_s

$$t_s \geq \left(\frac{2(t_i + t_{i+1}) \times P_{DL+LL}}{A_{re} \times F_s} \right) \geq 2 \text{ mm}$$

$$t_s \geq \left(\frac{2(0.0086 + 0.0086) \times 2.6}{0.10 \times (0.6 \times 274.4)} \right) = 6.0 \times 10^{-3} \text{ m = 5.71 mm}$$

$\therefore$ Use, t_s = 5.71 mm

Where, for A36 steel

$F_s = 0.6\ f_y = 0.6 \times 274.4$ MN/m^2, $A_{re} = 0.10$ m^2

- Total height 'h' of the bearing

Assume both the top and bottom cover plates as 2.5 cm thick.

$\therefore$ Total height of bearing is, h = t_r + N $\times$ ts + 2 $\times$ 2.5

= 12 cm + 14 $\times$ 5.71 mm + 2 $\times$ 2.5 cm = 25 cm

5.2.3 Check for shear strain and stability conditions

- Check for Shear Strain under Vertical load P_{DL+LL}

Shear strain under vertical load = $\gamma_{c,\ DL+LL} = 6 \times S \times \dfrac{P_{DL+LL}}{E_c \times A}$

$$= 6 \times 10 \times \frac{2.6}{511.75 \times 0.33}$$

$$= 0.92 \leq \frac{\varepsilon_b}{3} = \frac{500\%}{3} = 1.667$$

$\therefore$ OK

- Stability check

$$\sigma_c = \frac{P}{A} = \frac{2600}{0.33} = 7840 \text{ kN/ m}^2$$

$$\leq \sigma_c = \frac{G \times S \times L}{2.5 \times t_r} = \frac{(106 \times 10) \times 10 \times 0.25}{2.5 \times 0.12} = 8833.33 \text{ kN/ m}^2$$

$\therefore$ OK

- Check on Stability under Earthquake Load

Shear Strain condition including the Earthquake Effect

$P_{DL+LL+EQ}$ = 2225.01 kN = 2.22 MN

Strain due to compression, γ_{sc} = $\dfrac{6\times S\times P}{A_{re}\times E_c} = \dfrac{6\times 10\times 2.22}{0.19\times 511.75} = 1.37$

Strain due to Earthquake, γ_{eq} = $\dfrac{D_D}{t_r} = \dfrac{0.17}{0.12} = 1.41$

$$\therefore \vartheta = \frac{12\times D_D\times e}{b^2+d^2} = \frac{12\times 0.17\times(0.05\times 22.982)}{\left((16.04)^2+(22.982)^2\right)} = 0.0029$$

Strain due to Rotation, γ_{sr} = $\dfrac{B^2\times\vartheta}{2\times t\times t_r} = \dfrac{55^2\times 0.0029}{2\times 0.86\times 12} = 0.43$

$\therefore \gamma_{sc}+\gamma_{eq}+\gamma_{sr} = 3.23$

$< 0.75\varepsilon_b = 0.75\times 5 = 3.75$

$\therefore OK.$

- Check on Roll-out under Earthquake Load

$$\delta_{roll-out} = \frac{1}{2}\times\frac{P_{DL+LL+EQ}\times L}{P_{DL+LL+EQ}+k_{eff}\times h}$$

$$= \frac{1}{2}\times\frac{2225.01\times 0.55}{2225.01+(1674.11\times 0.25)}$$

$= 231.46$ mm

$> D_D = 210$ mm

$\therefore Safe$

5.2.4 Design Results - Dimensions of High Damping Rubber Bearing

The design result for High damping rubber bearings is shown here in a tabular form in TABLE 5.2.

TABLE 5.2 DESIGN RESULTS FOR HIGH DAMPING RUBBER BEARING (mm)

Length of bearing, L	250
Width of bearing, B	550
Total height of bearing, h	250
No. of rubber layers, N	14
Thickness of individual rubber layers, t	8.6
Number of steel plates, N_s	14
Thickness of individual steel plates, t_s	5.71
Thickness of top and bottom cover plates	25

A figure consisting of above mentioned properties is shown in FIGURE 5.2.

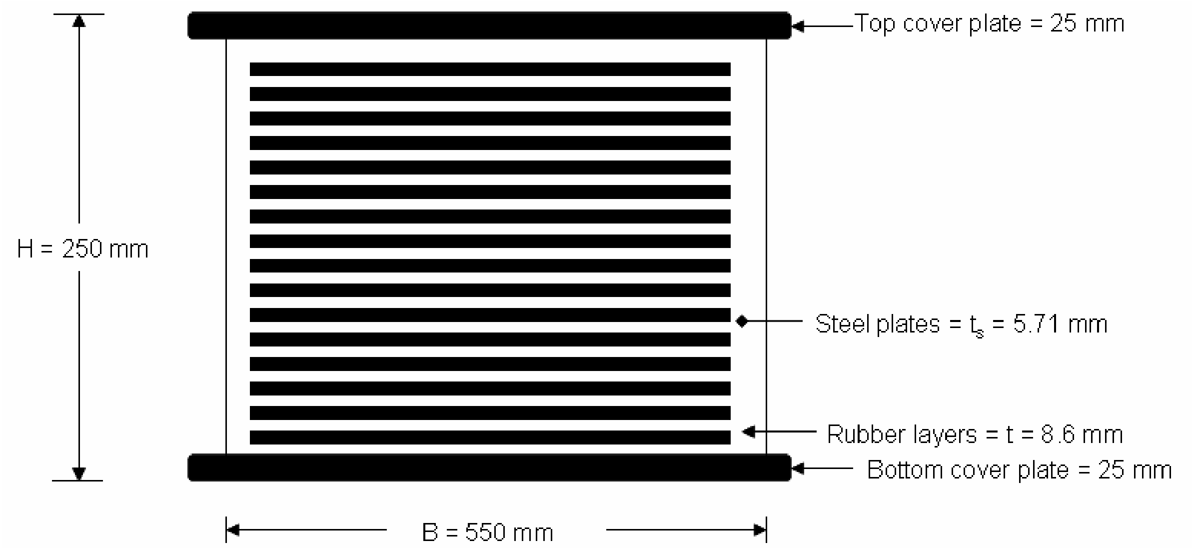


FIGURE 5.2 DIMENSIONS OF HIGH DAMPING RUBBER BEARING

5.3 DESIGN OF FRICTION PENDULUM SYSTEM

Design Data

i) Target period, T_D = 2.5 sec;

ii) Friction coefficient of the spherical sliding surface of Friction pendulum system = μ = 0.06;

iii) Design horizontal displacement = D = 12 cm.

iv) For effective damping ratio, ξ_{eff} = 20 %, B_D i.e. Damping coefficient = 1.5 [from Table 1623.2.2.1 – IBC 2000] and

v) Seismic coefficient, S_D = 0.4 considering site condition of isolated building with long periods.

5.3.1 Design

- Determine the size of Friction Pendulum System

Radius of curvature of spherical sliding surface of the isolation is,

$$R_{FPS} = g\left(\frac{T_D}{2\Pi}\right)^2 = 9.81\left(\frac{2.5}{2\Pi}\right)^2 = 1.55\, m$$

$\therefore$ Use, R_{FPS} = 1.6 m

- Determine the total effective stiffness of Isolation system

$$\Sigma\, k_{eff} = \frac{W_T}{R_{FPS}} + \frac{\mu W_T}{D} = \frac{30238.5}{1.6} + \frac{0.06 \times 30238.5}{0.2} = 27970.61 \text{ kN/m}$$

Thus, average effective stiffness k_{eff} for a single FPS isolator is

$$\frac{27970.61}{2} = 13985.3 \text{ kN/m}$$

- Determine the effective damping ξ_{eff} for FPS

The effective damping ξ_{eff} provided by isolator depends on the design displacement D_D, which can be computed as,

$$\xi_{eff} = \frac{2}{\Pi}\frac{\mu}{\left(\mu + \frac{D}{R}\right)} = \frac{2}{\Pi}\frac{0.06}{\left(0.06 + \frac{0.2}{1.6}\right)} = 0.206 = 20.65\%$$

5.3.2 Check the design displacement D_D

$$D_D = \left(\frac{g}{4\Pi^2}\right)\frac{S_D \times T_D}{B_D} = \left(\frac{9.81}{4\Pi^2}\right)\frac{0.4 \times 2.5}{1.5} = 0.17\, m \quad < \quad 0.20\, m$$

$\therefore$ OK.

- Estimate of vertical displacement δ_v

$$\delta_v = \frac{D^2}{2 \times R_{FPS}} = \frac{0.2^2}{2 \times 1.6} = 0.0125 \text{ m = 1.25 cm}$$

Use depth δ = 1.7 cm for the disk.

Use diameter d = 45 cm for the disk of FPS (> 2D)

Check: - $\dfrac{\left(\dfrac{d}{2}\right)^2}{2 \times R_{FPS}} = \dfrac{\left(\dfrac{0.45}{2}\right)^2}{2 \times 1.6} = 0.016\, m \; > \; 0.013\, m$

∴ OK

5.3.3 Check on the recentering condition for the earthquake load case

$$\frac{D}{R_{FPS}} = \frac{0.2}{1.6} = 0.125 \geq \mu = 0.06$$

∴ OK

5.3.4 Design results: - Dimensions for Friction Pendulum System

The design result for Friction pendulum system is shown here in a tabular form in TABLE 5.3.

TABLE 5.3 DESIGN RESULTS FOR FRICTION PENDULUM BEARING (mm)

Radius of curvature of the spherical surface, R_{FPS}	1600
Depth of the disk, δ	17
Diameter of the disk, d	450

A figure consisting of abovementioned properties is shown in FIGURE 5.3.

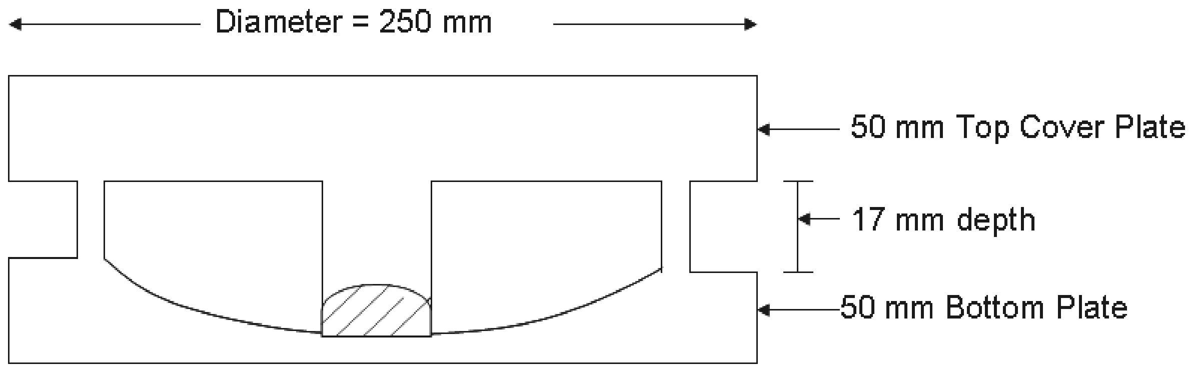


FIGURE 5.3 DIMENSIONS OF FPS

Summary

The chapter has primarily dealt with design of three different types of bearings namely Lead rubber bearings, High damping rubber bearings and Friction pendulum system & design outcome of bearing were listed in table 5.1, 5.2 and 5.3 respectively. As every column of building has to carry different amount of axial load, design of bearing for an individual column leads to a very complex task. Hence, column with 15 % of load difference were grouped together to arrive at some bearing design. On subsequent exercise, it has been found that design of bearings is not much influenced by amount of load it has to carry. Hence it was decided to provide same bearing underneath of every column of same dimension; however this will lead to uneconomical design in project. The other point of view is that, if bearing is designed for an individual column it will lead uneven height of bearing, which will add complexity to the construction of the same. Hence, keeping economy aside common unique bearing were design for all columns.

6. R.C.C BUILDING – BASE ISOLATED

The modeling & analysis of fixed base building was taken care of in chapter 4 which includes different modeling aspect under consideration. The modeling and analysis of Base Isolated RCC building is a challenging task including seismic analysis of RCC building. A care has been taken to incorporate proper modeling of each component.

6.1 GEOMETRY OF BUILDING

The geometry of the base isolated RCC building is same as that of a fixed base RCC building, except that an addition of isolators at appropriate locations as shown in chapter 3, section 3.1; isolator can be suitably placed at different locations of building, depending upon the requirements. However, mostly isolators are placed at the base of the building to safeguard entire building from an earthquake ground motion. The issue that comes forward is how to model isolator and where to locate it. Looking to this issue proper understanding of building behavior is must.

Isolation is generally provided at the base of the building with a provision of seismic gap all around the building for the purpose of maintenance & for displacement of building in an event of earthquake. Providing isolation at the base of the building, flexibility is incorporated at the base & simultaneously building is entirely gets isolated. Considering this aspect of base isolation at least two different models was thought off for the building.

The first model of base isolated RCC building is traditional, where bearing was provided at the base (level of footing) of the building. This model considers entire building into analysis including rigid RC wall at basement level. Only, issue need to take care off is, building should have sufficient space at the base to undergo permitted displacement of bearings.

The second model of base isolated RCC building is based on the fact that, as it has been seen that while analyzing fixed based RCC building because of stiff mass at basement level the building is not building the response and mass participation more than 90% was achieved through 10th mode of it's vibration. This spurs the thought that, as for initial modes the mass which was not participating can be cut off in analysis and isolator can reasonably placed at the top of basement column & hence, this represent the idealized mathematical model for base isolated RCC building. Thus, second model was derived based on above mentioned concept a bearing at the top of the column at basement level. Totally, two model of base isolated RCC building along with all three bearing namely LRB, HDR & FPS.

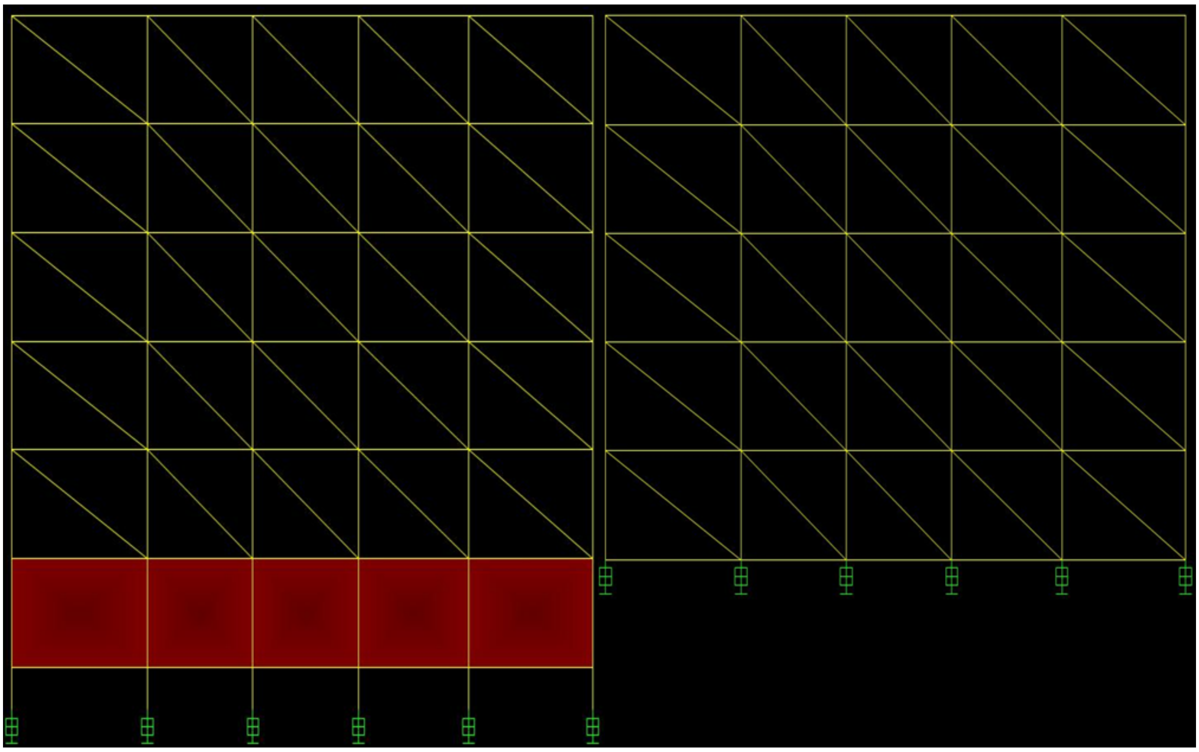


FIGURE 6.1 BEARINGS PROVIDED AT THE BASE OF BUILDING **FIGURE 6.2 BEARINGS PROVIDED AT THE TOP OF BASEMENT COLUMN**

Figure 6.1 shows the provision of the bearing at the base of the building where the basement is also modeled. Figure 6.2 shows the provision of the bearing at the top of the basement column, where the basement part has not been modeled.

6.1.1 MATERIAL PROPERTIES

Material properties for beams, columns, walls and struts remain same as that for the fixed base building. The material properties incorporated for bearings in SAP2000 are shown in TABLE6.1. The material properties for the bearings were selected from the IBC 2000 provisions.

TABLE 6.1 MATERIAL PROPERTIES FOR BASE ISOLATED BUILDING

Description	LRB	FPS	HDR
Rubber Hardness	IRHD 70	-	IRHD 60
Young's Modulus, E (N/cm^2)	735	-	445
Shear Modulus, G (N/cm^2)	173	-	106
Modified Factor, k	0.53	-	0.57
Elongation at break, ϵ_b (%)	500	-	500

- **Boundary Condition**

In this analysis all the nodes at the base are isolated for movement in x, y and z directions as shown in Figure 6.1.

- **Sectional Properties**

All the sectional properties for beams, columns, walls and struts are same as used for base fixed condition.

- **Diaphragm Constraint**

All the slabs were assigned diaphragm constraints in lateral direction so as to have a rigid body action.

6.2 MODELING OF ISOLATOR

It has been seen that the building under consideration consist of a rigid RCC wall at the basement of the building, which result in higher frequency excitation requirement. The free vibration analysis of fixed base RCC building has prominently indicated less mass participation in initial modes of vibration as stiff mass at basement doesn't allow the building to vibrate. It has been obtained as per the code requirement 90 % mass participation satisfies in the 10th mode of vibrations, till that the rigid basement doesn't participate at all.

This prompted work to bifurcate into two case of isolator location.

1. Building with isolator at the base of the building.
2. Building with isolator at the top of the basement column.

The schematic view of base isolator is as shown in FIGURE 6.1 and 6.2 respectively. The later model provides a flexibility of outer portion below top of basement column, as it acts rigidly during the analysis.

The modeling of the building remains same as shown in chapter 4. Bearings were additionally modeled in the analysis of base isolated structure and so modeling of bearings given here. Both the models were modeled using same properties only the location was changed so as to see the response in both the cases.

The modeling of the bearings in SAP2000 link element was used which provides the facility for the provision of properties of bearings in to the software. In that Rubber Isolator was used to model Lead Rubber Bearing (LRB) and High Damping Rubber bearing (HDR), while sliding isolator was used to model Friction Pendulum System (FPS). The properties incorporated in SAP2000 for the bearings are as shown in TABLE 6.2.

TABLE 6.2 PROPERTIES OF BEARINGS INCORPORATED IN SAP2000

Description	LRB	FPS	HDR
Effective Horizontal Stiffness, K_{eff} (kN/m)	1674.11	13985.30	1674.11
Short term Yield force, Q_d (kN)	55.17	-	55.17
Post Yield Horizontal Stiffness, k_d (kN/m)	1411.39	-	1411.39
Radius of Curvature of Spherical Sliding Surface, R_{FPS} (m)	-	1.6	-
Effective Damping, ξ_{eff} (%)	-	20	20

6.3 ANALYSIS IN SAP2000

Two types of analysis were carried out in SAP2000 for the isolated building.

1. Static Analysis
2. Dynamic Analysis (Response Spectrum Analysis)

The loads considered for static and dynamic analysis remains same as done for fixed base building in chapter 4.

As per the specifications of IBC 2000, Dynamic Analysis (Response Spectrum Analysis) was carried out for the base isolated condition. Figure 6.3 shows how the response spectrum analysis case was defined for the base isolated building in SAP2000. Modal combination was done using CQC method and directional combination was done using SRSS method.

For earthquake analysis, Response Spectrum Cases is to be defined as the software doesn't supports IS 1893-2002. The response spectrum given in IS 1893-2002 for 5% damping is defined and same is to be used for performing Response Spectrum Analysis. The modal combination options available with the software are Complete Quadratic Combination (CQC), Square Root of the Sum of the Squares (SRSS), Absolute Method (ABS) and General Modal Combination (GMC) method. Modal combination produces a single, positive result for each direction of acceleration. These directional values are combined to produce a single, positive result. There are two options available for the directional combination: SRSS and ABS as shown in FIGURE 6.3

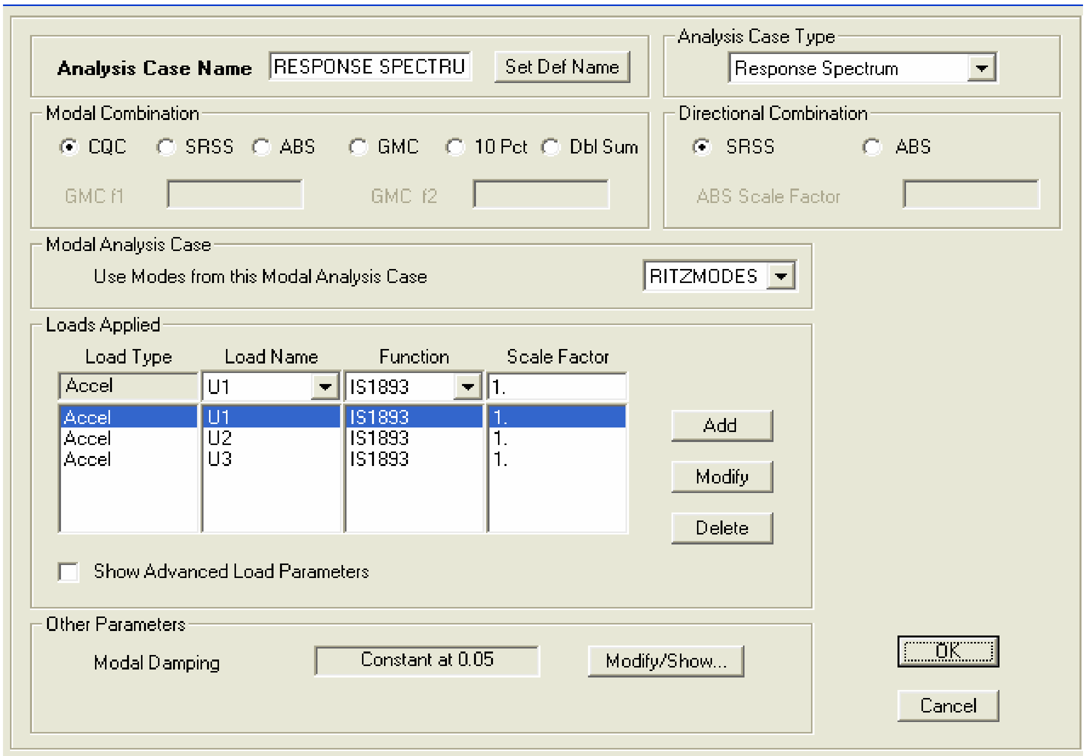


FIGURE 6.3 RESPONSE SPECTRUM DEFINITIONS IN SAP2000

6.4 OUTPUT OF ANALYSIS

After carrying out the dynamic response spectrum analysis results were obtained. TABLE 6.3 to 6.8 gives the results for all the three bearings viz. LRB, HDR & FPS for the two locations of the bearings in the form of modal time periods and mode shapes. Other results are presented and discussed in chapter 7.

TABLE 6.3 MODE SHAPES FOR LEAD RUBBER BEARING AT BASE OF BUILDING

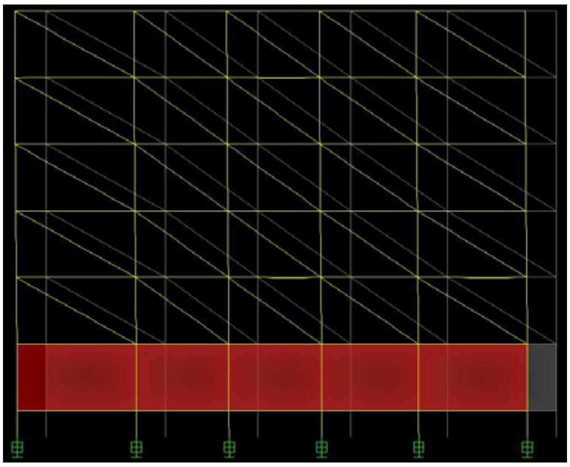
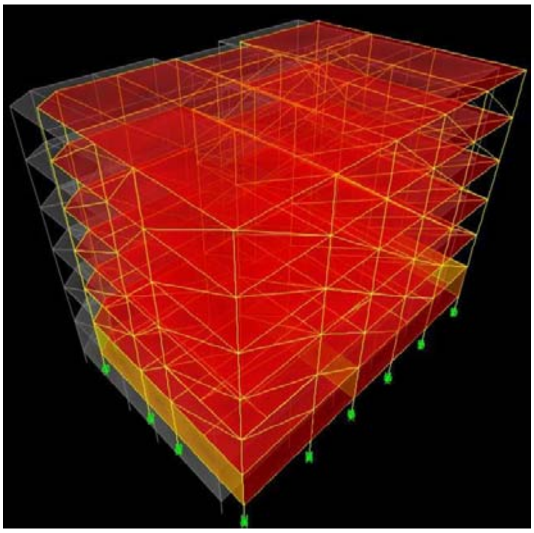
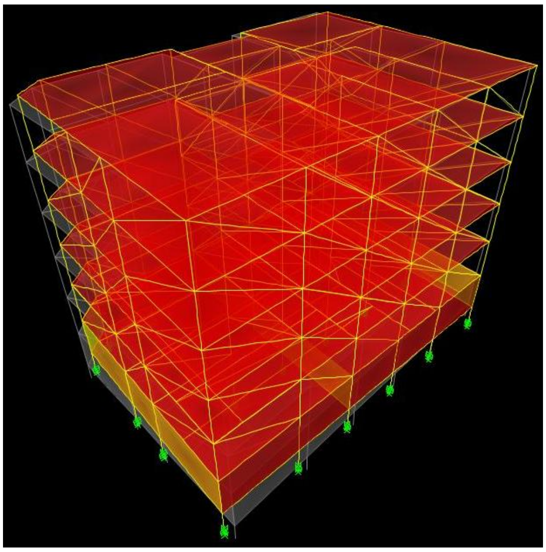
Mode No.	Time Period [seconds]	Mode Shape	Mode of vibration
1	1.65		X-direction
2	1.60		Y-direction
3	1.55		Torsion

TABLE 6.4 MODE SHAPES FOR LEAD RUBBER BEARING AT TOP OF BASEMENT COLUMN

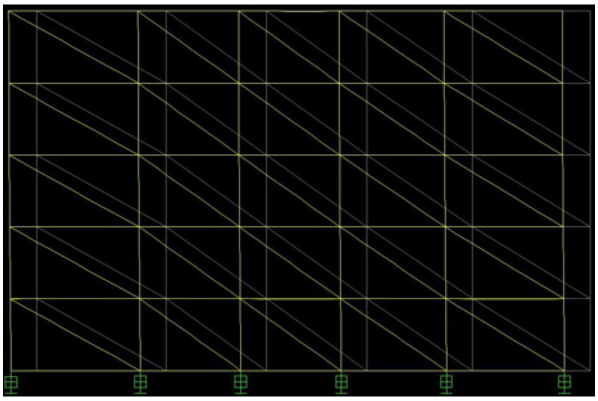
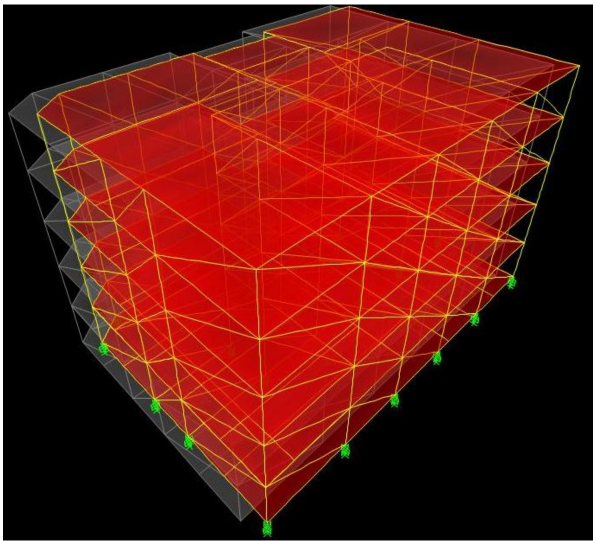
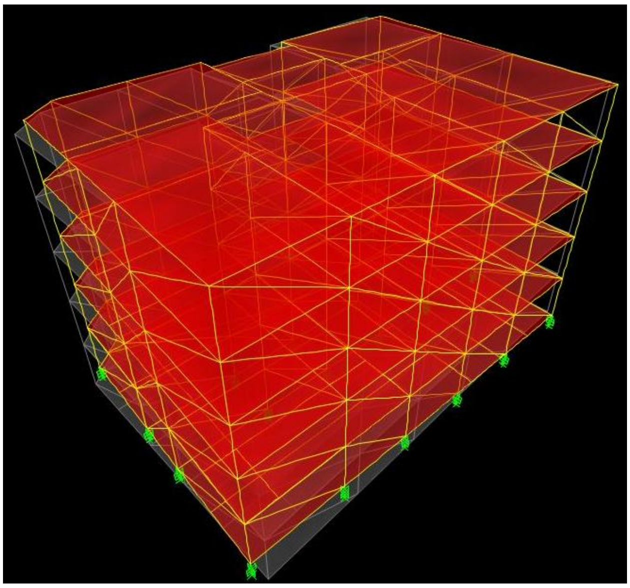
Mode No.	Time Period [seconds]	Mode Shape	Mode of vibration
1	1.52		X-direction
2	1.48		Y-direction
3	1.42		Torsion

TABLE 6.5 MODE SHAPES FOR FRICTION PENDULUM SYSTEM AT BASE OF BUILDING

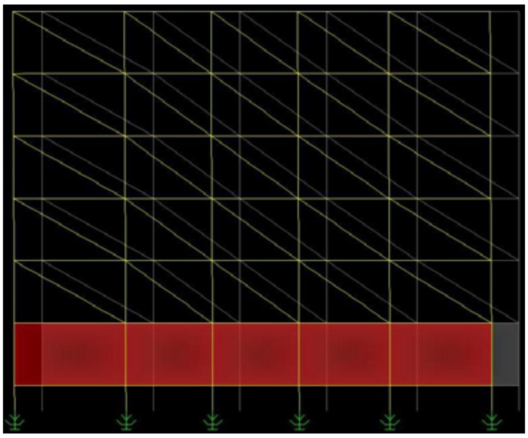
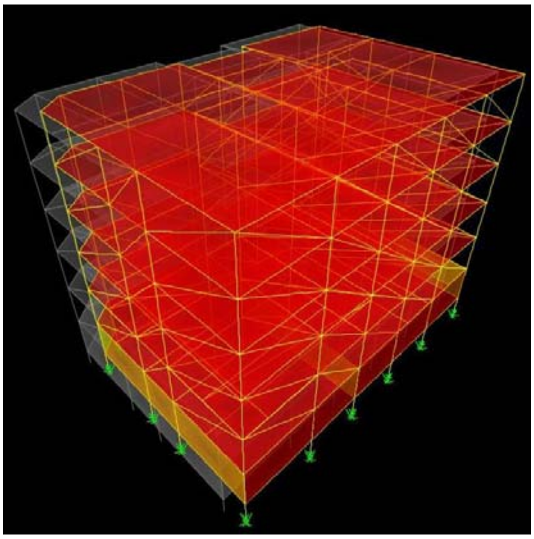
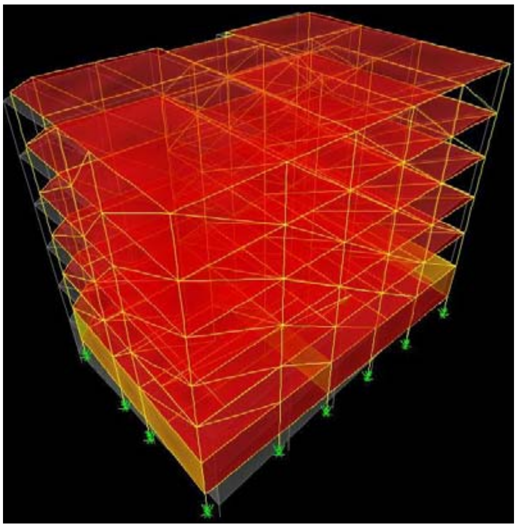
Mode No.	Time Period [seconds]	Mode Shape	Mode of vibration
1	1.64		X-direction
2	1.60		Y-direction
3	1.53		Torsion

TABLE 6.6 MODE SHAPES FOR FRICTION PENDULUM SYSTEM AT TOP OF BASEMENT COLUMN

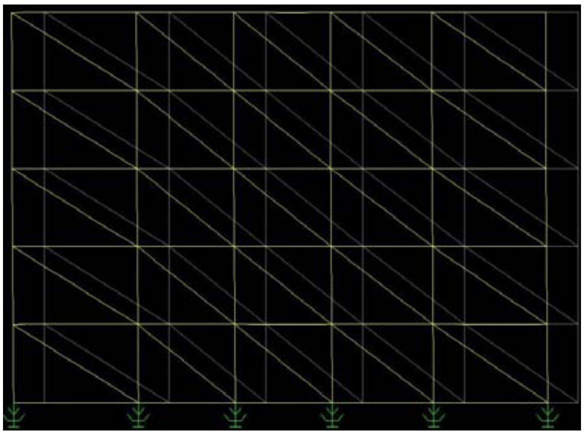
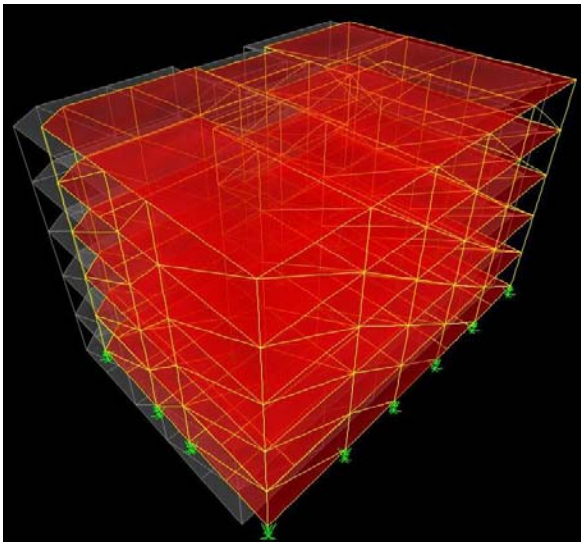
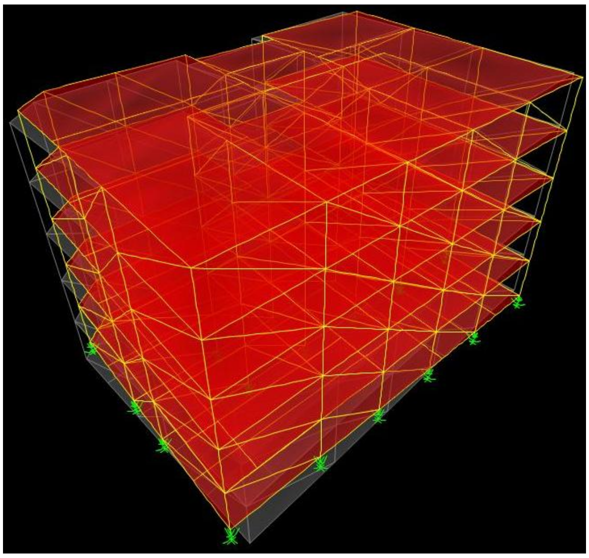
Mode No.	Time Period [seconds]	Mode Shape	Mode of vibration
1	1.51		X-direction
2	1.48		Y-direction
3	1.40		Torsion

TABLE 6.7 MODE SHAPES FOR HIGH DAMPING RUBBER AT BASE OF BUILDING

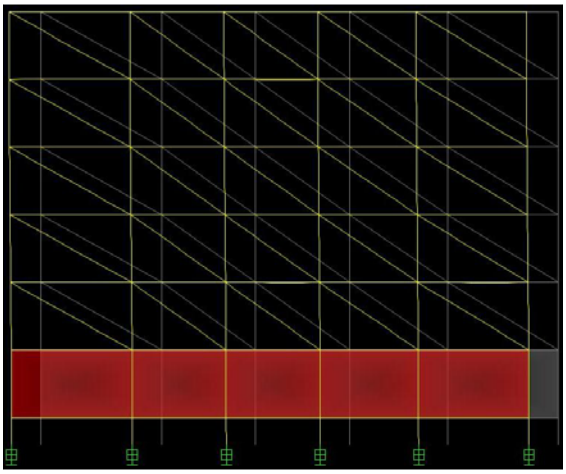
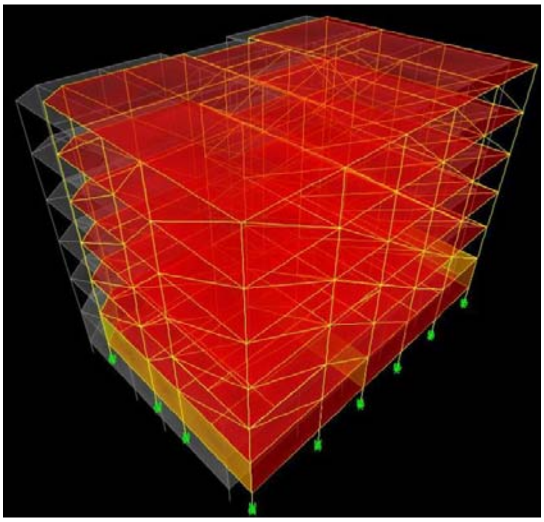
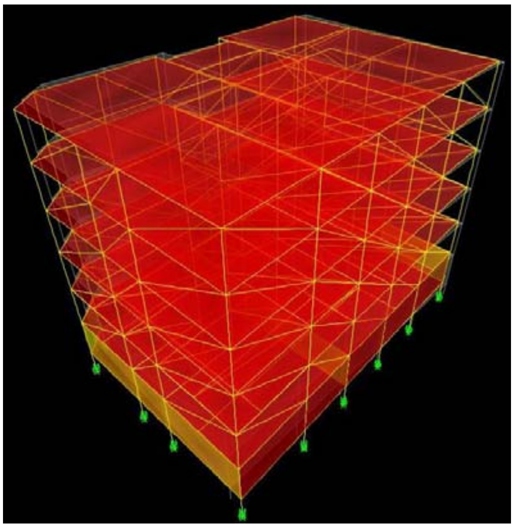
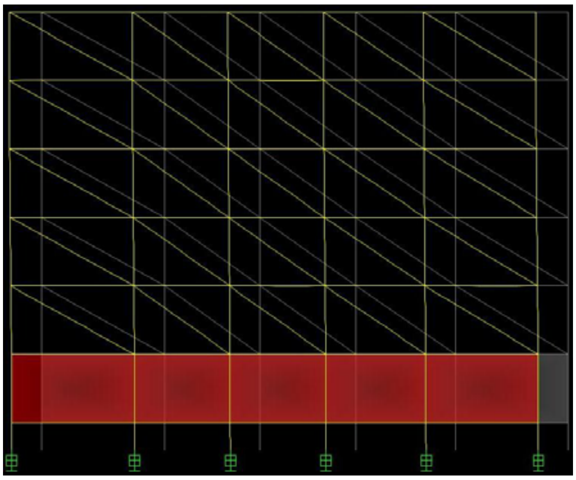
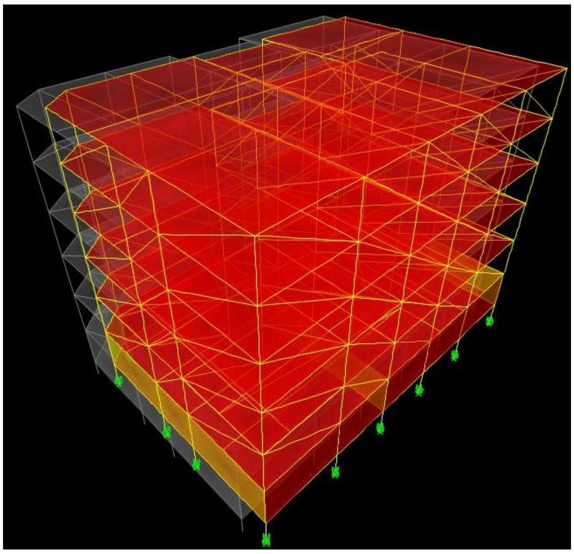
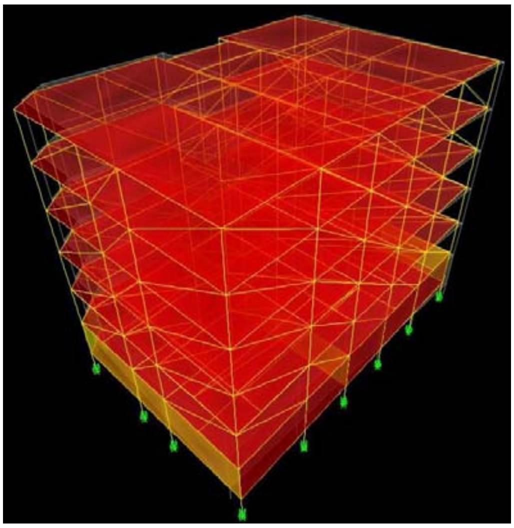
Mode No.	Time Period [seconds]	Mode Shape	Mode of vibration
1	1.62		X-direction
2	1.57		Y-direction
3	1.52		Torsion

TABLE 6.8 MODE SHAPES FOR HIGH DAMPING RUBBER AT THE TOP OF BASEMENT COLUMN

Mode No.	Time Period [seconds]	Mode Shape	Mode of vibration
1	1.49		X-direction
2	1.45		Y-direction
3	1.39		Torsion

7. RESULTS & DISCUSSIONS

After carrying out the dynamic analysis for fixed base and isolated base building, the results obtained are compared & discussed here. Table 7.1 gives the comparison of modal periods for fixed base and isolated base.

TABLE 7.1 COMPARISON OF MODAL PERIOD

Modal Periods (sec)							
	Base Fixed	Base Isolated (Bearings)					
		Lead Rubber Bearings		Friction Pendulum System		High Damping Rubber	
Mode		Basement	Base	Basement	Base	Basement	Base
1	0.42	1.52	1.65	1.51	1.64	1.49	1.62
2	0.40	1.48	1.60	1.48	1.60	1.45	1.57
3	0.34	1.42	1.55	1.40	1.53	1.39	1.52
4	0.14	0.23	0.26	0.21	0.21	0.23	0.26
5	0.14	0.22	0.25	0.19	0.20	0.22	0.25
6	0.09	0.19	0.20	0.07	0.08	0.19	0.20
7	0.08	0.10	0.09	0.03	0.02	0.10	0.09
8	0.08	0.10	0.08	0.02	0.02	0.10	0.08
9	0.07	0.08	0.07	0.02	0.01	0.08	0.07
10	0.05	0.08	0.05	0.02	0.01	0.08	0.05
11	0.05	0.06	0.05	0.02	0.01	0.06	0.05
12	0.04	0.06	0.03	0.01	0.01	0.06	0.03

- One of the main criteria for base isolation is that the time period of a base isolated structure should be at least three times higher than that of a fixed base building.
- From the results available in Table 7.1 we can clearly see that the time period for a base isolated structure is three times higher than that of a fixed base structure.

Hence, we can clearly see that one criterion for base isolation is achieved over here.

The bearings were proposed to be installed at two different locations in the building;

1. at the base of the building
2. at the top of the basement column

In the table 7.1 the basement written under LRB, HDR & FPS bearings signifies the locations of bearings at the top of basement column. Where as, base written under LRB, an HDR & FPS bearing signifies the locations of bearings at the base of the building.

From TABLE 7.1 we can see that

1. The provision of the bearing at the base of the building isolates the entire building and hence initial time period obtained is on higher side as compared to the provision of bearings on the top of the basement column.
2. Mode 1 and mode 2 here gives the 1st fundamental mode in X and Y direction, while mode 3 gives torsion. Similarly mode 4 and 5 are 2nd fundamental mode in X and Y direction and so on.
3. From the third mode the time period for fixed base and base isolated condition doesn't vary much. It means that for higher modes the time period of base isolated structure is almost same as that for a fixed base building, which is because higher modes are not contributing much to the mass participation.

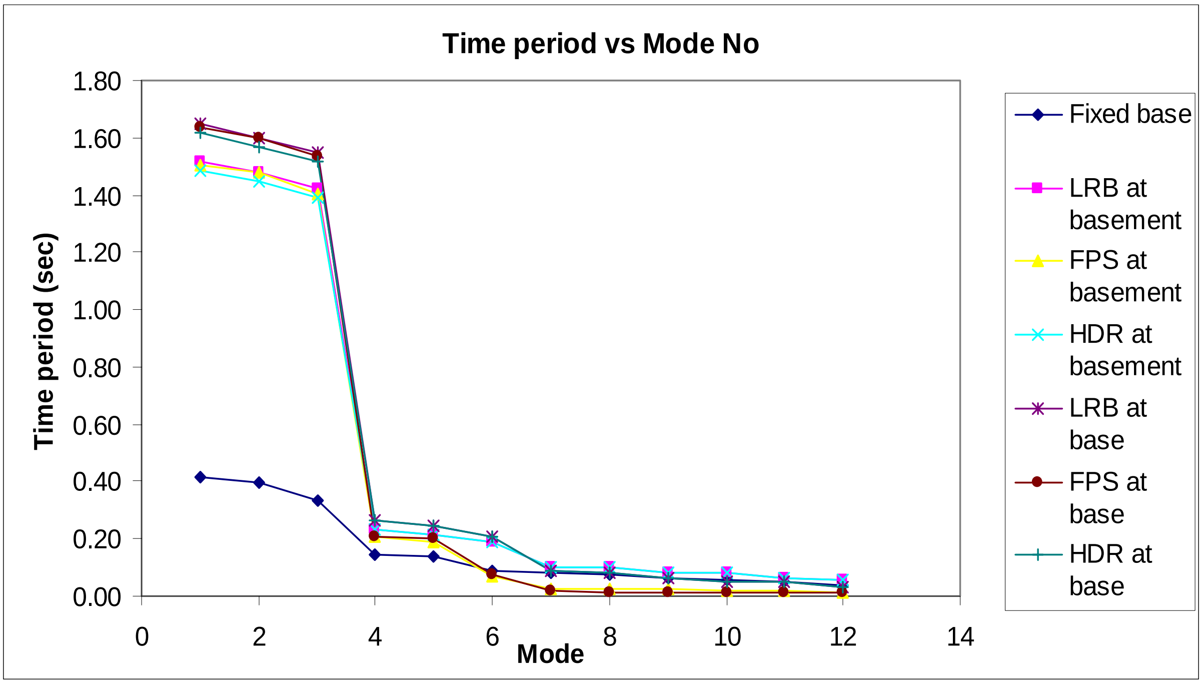


FIGURE 7.1 COMPARISON OF TIME PERIOD VS. MODE NO

FIGURE 7.1 is a graphical presentation of time period vs. mode no for a fixed base and isolated base building as taken from TABLE 7.1. The graph clearly shows the period shift that we are able to achieve due to base isolation in the initial modes. We can see there is considerable period shift which is obtained because of the provision of flexibility at the base of the structure due to base isolation.

FIGURE 7.2 & 7.3 shows the comparison of mode 1 in X direction for fixed base and isolated base respectively. From the figure it is clear that fixed base building deforms in a triangular pattern along its height where as a base isolated building deforms in a rectangular pattern along its height. Thus deformed shape clearly demonstrates that isolation is achieved as shown in FIGURE 7.3.

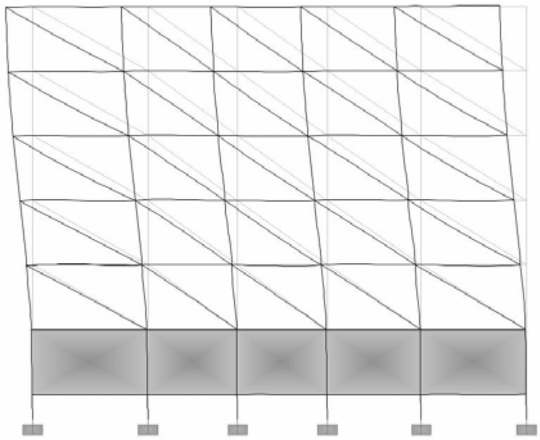


FIGURE 7.2 MODE 1 IN X DIRECTION FIXED BASE

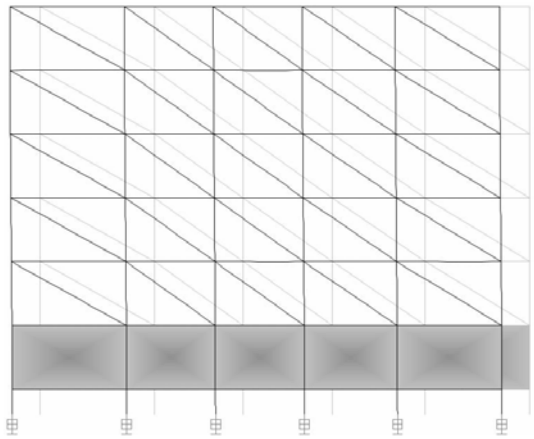


FIGURE 7.3 MODE 1 IN X DIRECTION BASE ISOLATED

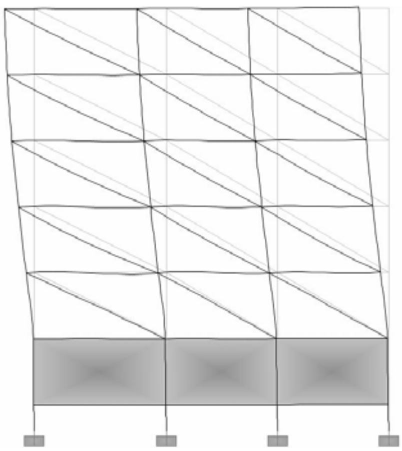


FIGURE 7.4 MODE 2 IN Y DIRECTION FIXED BASE

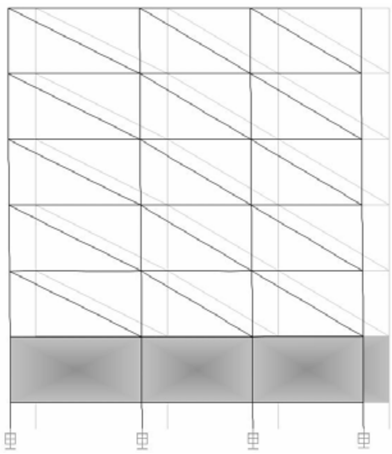


FIGURE 7.5 MODE 2 IN Y DIRECTION BASE ISOLATED

Similarly FIGURE 7.4 & 7.5 shows the comparison of mode 2 in Y direction for fixed base and isolated base respectively. The deformation observed in mode 2 in fixed base and isolated base in Y direction is similar to that observed in mode 1 in X direction in fixed base and isolated base respectively.

Table 7.2 gives the comparison of modal participating mass ratios for fixed base and isolated base building in X direction.

TABLE 7.2 COMPARISON OF MODAL PARTICIPATING MASS RATIO IN X DIR

Summation in X direction (Unitless)							
	Base Fixed	Base Isolated (Bearings)					
		Lead Rubber		Friction Pendulum System		High Damping Rubber	
Mode		Basement	Base	Basement	Base	Basement	Base
1	0.63	0.35	0.38	0.43	0.48	0.35	0.38
2	0.63	0.78	0.71	0.85	0.78	0.78	0.71
3	0.64	1.00	1.00	1.00	1.00	1.00	1.00
4	0.77	1.00	1.00	1.00	1.00	1.00	1.00
5	0.77	1.00	1.00	1.00	1.00	1.00	1.00
6	0.84	1.00	1.00	1.00	1.00	1.00	1.00
7	0.84	1.00	1.00	1.00	1.00	1.00	1.00
8	0.84	1.00	1.00	1.00	1.00	1.00	1.00
9	0.84	1.00	1.00	1.00	1.00	1.00	1.00
10	0.99	1.00	1.00	1.00	1.00	1.00	1.00
11	0.99	1.00	1.00	1.00	1.00	1.00	1.00
12	0.99	1.00	1.00	1.00	1.00	1.00	1.00

IS 1893-2002 Part I specifies that the number of modes to be used in the analysis should be such that the sum total of modal masses of all the modes considered is at least 90 % of the total seismic mass and missing mass correction beyond 33 %.

In Table 7.2 we can see that the mass participation of 90 % as per IS -1893 takes part in the 10th mode. This is because of the presence of RCC wall all around the periphery and interior of the building. The RCC walls were modeled as solid walls around the periphery and interior of building at the basement level and due to the presence of RCC walls the building becomes very stiff at the basement level and hence higher frequency is required for the mass participation. While in case of base isolated the modal mass participation of 100% is achieved in 3rd mode because of the flexibility provided by the bearings.

Table 7.3 gives the comparison of modal participating mass ratios for fixed base and isolated base building in Y direction.

TABLE 7.3 COMPARISON OF MODAL PARTICIPATING MASS RATIO IN Y DIR

Summation in Y direction (Unitless)							
	Base Fixed	Base Isolated (Bearings)					
Mode		Lead Rubber		Friction Pendulum System		High Damping Rubber	
		Basement	Base	Basement	Base	Basement	Base
1	0.00	0.25	0.15	0.30	0.18	0.25	0.15
2	0.64	0.82	0.82	0.88	0.87	0.82	0.82
3	0.66	1.00	1.00	1.00	1.00	1.00	1.00
4	0.66	1.00	1.00	1.00	1.00	1.00	1.00
5	0.77	1.00	1.00	1.00	1.00	1.00	1.00
6	0.77	1.00	1.00	1.00	1.00	1.00	1.00
7	0.80	1.00	1.00	1.00	1.00	1.00	1.00
8	0.81	1.00	1.00	1.00	1.00	1.00	1.00
9	0.82	1.00	1.00	1.00	1.00	1.00	1.00
10	0.82	1.00	1.00	1.00	1.00	1.00	1.00
11	0.99	1.00	1.00	1.00	1.00	1.00	1.00
12	0.99	1.00	1.00	1.00	1.00	1.00	1.00

In Table 7.3 the mass participation of 90 % or more is achieved in the 11th mode in Y direction and that is due to the provision of RC walls at the basement level.

In Table 7.2 and Table 7.3 we can see that mass participation of 90 % in case of base isolated structure is obtained in the third mode, and so as per IS 1893-2002 Part I we shall consider only first three modes for the response spectrum analysis of the building and hence results for displacement and storey drift for building is plotted for the first three modes respectively.

One other criteria for the effective working of the base isolation system is the reduction in the base shear that we must achieve in X and Y direction (two horizontal directions). TABLE 7.4 shows the comparison of base shear for fixed and isolated base in X direction. Reduction in base shear signifies the reduction in storey shear resulting in to reduction of storey drift. Hence, the building will not undergo large displacements and thus, the damage is reduced.

From Table 7.4 we can see that the base shear obtained for fixed base is reduced to almost 62 - 66 % for isolated base. Thus, another criterion for effective working of base isolators is achieved here. We can see that the values of base shear are on conservative side for bearings located at the top of the basement column of the building as compared to the bearings placed at the base of the building.

TABLE 7.4 COMPARISON OF BASE SHEAR IN X DIRECTION

Base Shear In Global X direction (kN)						
Base Fixed	**Base Isolated (Bearings)**					
	Lead Rubber		**Friction Pendulum System**		**High Damping Rubber**	
	Basement	**Base**	**Basement**	**Base**	**Basement**	**Base**
2964	1019	1100	1029	1120	1038	1121
Percentage Reduction in Base Shear						
	%	%	%	%	%	%
	66	63	65	62	65	62

Figure 7.6 shows the graphical comparison of base shear for a fixed base building with isolated building in X direction. We can see from the graph that the value of base shear for bearings at the base of the building is higher as compared to that of bearings placed at the top of the basement column. Base shear value coming higher in case of fixed base building is due to the rigid body action taking place. Even the percentage reduction of base shear in case of bearings at the top of the basement column is more.

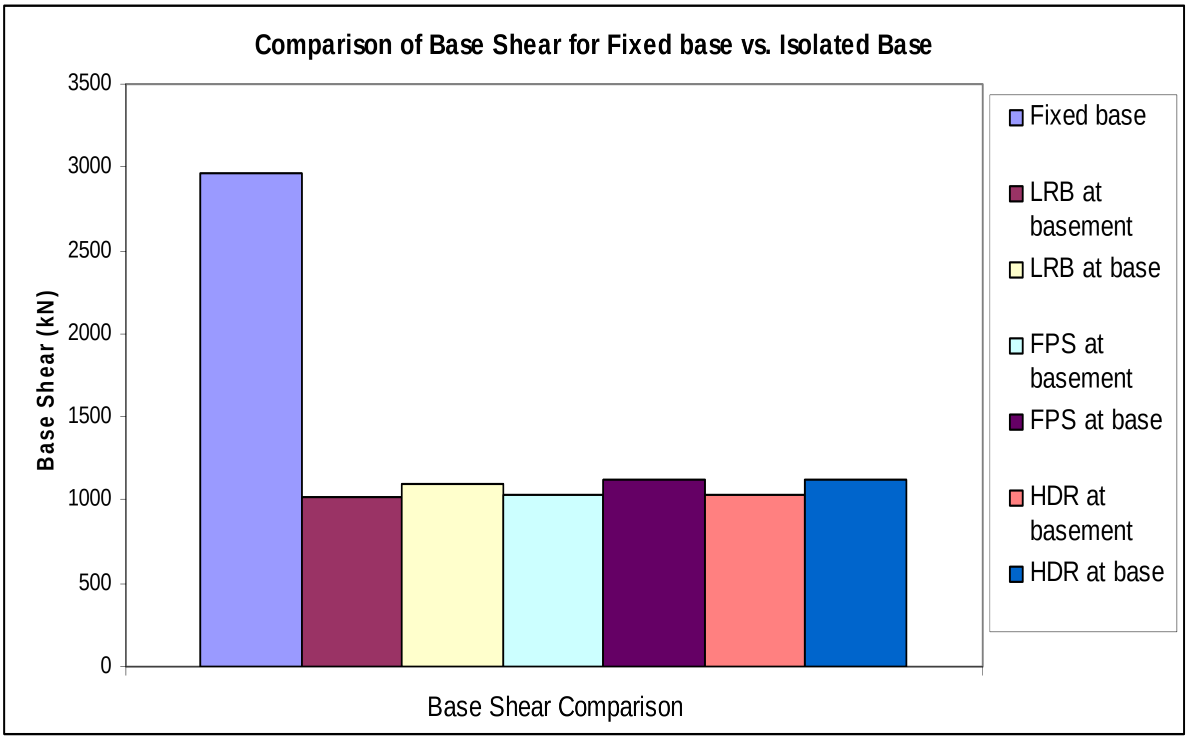


FIGURE 7.6 COMPARISON OF BASE SHEAR IN X DIRECTION

Similarly Table 7.5 gives the comparison of base shear in Y direction. We can see that similar results as achieved in X direction are observed in the Y direction for base isolated structure as compared to fixed base structure. The reduction in base shear is almost 63 – 67 % as compared to fixed base RCC building.

TABLE 7.5 COMPARISON OF BASE SHEAR IN Y DIRECTION

Base Shear In Global Y direction (kN)						
Base Fixed	**Base Isolated (Bearings)**					
	Lead Rubber		**Friction Pendulum System**		**High Damping Rubber**	
	Basement	**Base**	**Basement**	**Base**	**Basement**	**Base**
3089	1030	1130	1038	1150	1049	1152
Percentage Reduction in Base Shear						
	%	%	%	%	%	%
	67	63	66	63	66	63

FIGURE 7.7 gives the graphical presentation for comparison of base shear of fixed base RCC structure with base isolated structure along Y direction. We can see that almost similar results are obtained for the base shear as compared to that obtained in X direction.

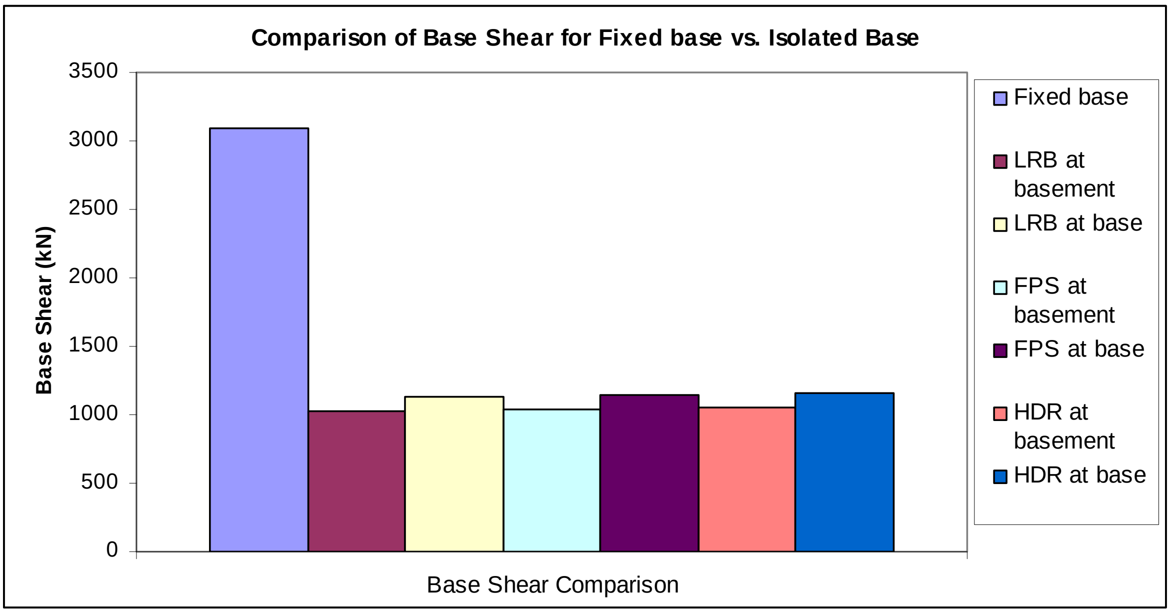


FIGURE 7.7 COMPARISON OF BASE SHEAR IN Y DIRECTION

The storey level 0 in FIGURE 7.8 means the base level of the building, storey level 1 means the basement floor level and likewise.

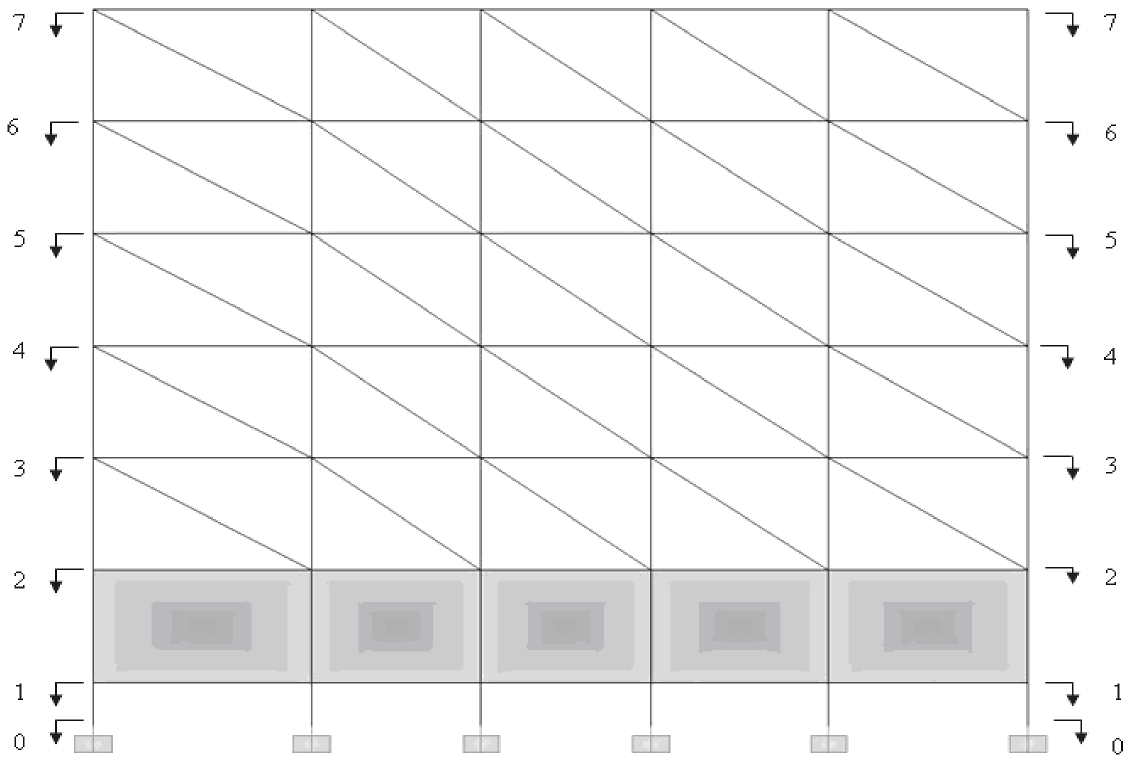


FIGURE 7.8 STOREY LEVELS IN THE BUILDING

FIGURE 7.9 shows the numbering of columns in the building in plan. For the purpose of comparisons of results column 1 is taken in to considerations as shown in Figure 7.9.

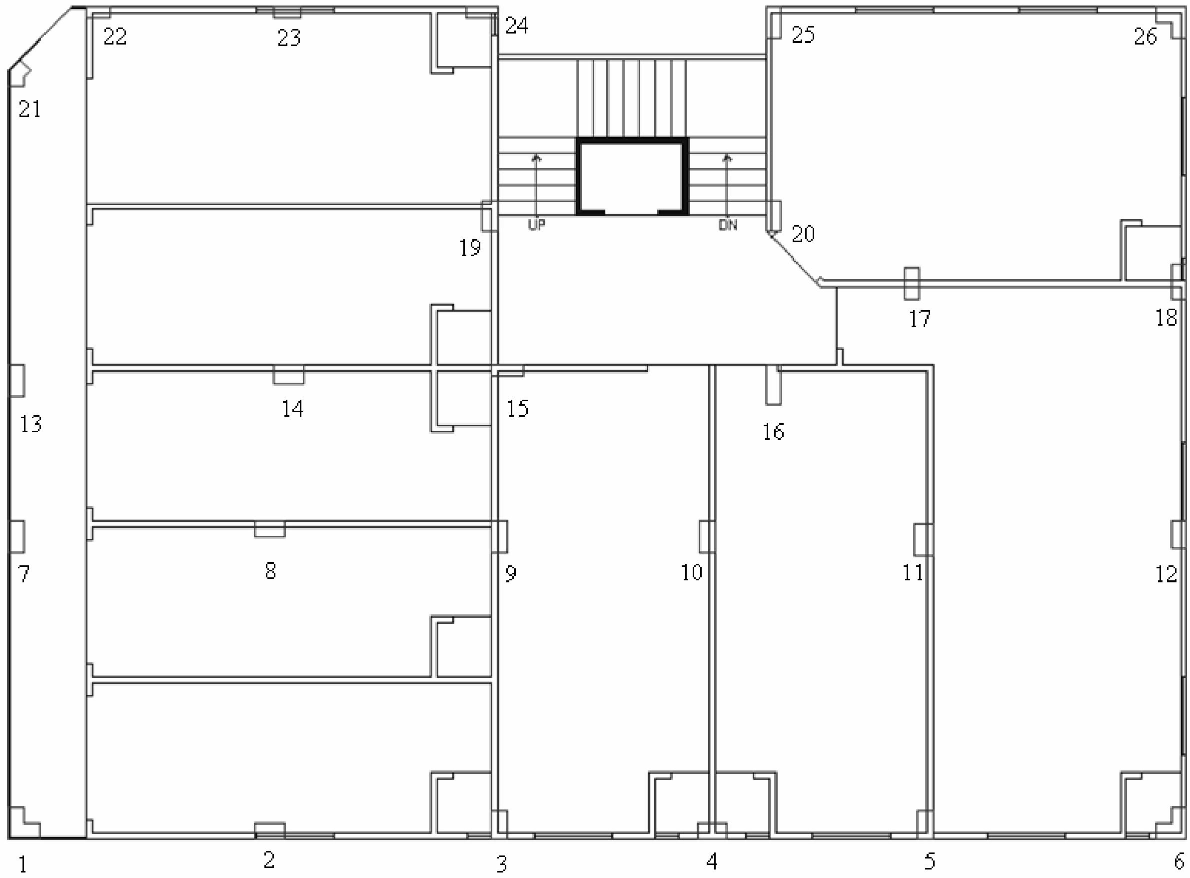


FIGURE 7.9 COLUMNS NUMBERING IN THE BUILDING

In modeling for the bearings at the top of the basement column the region below the bearings i.e. the basement region, is neglected. Hence in the result table the values are not presented.

Table 7.6 gives the comparison of displacement of column no 1 for mode 1 in X direction for different storey levels. We can see that the displacement at the top of the building in case of fixed base building is very high compared to that of a base isolated RCC building.

From Table 7.6 it is clear that the displacement at the base of the building is below 30 mm in case of base isolated building which is far below the allowable value of displacement for each bearing. Hence chances of collision with the other buildings are not there.

As we move from ground floor to the top floor in case of fixed base building the displacement values changes consistently, while in case of the base isolated building the displacement doesn't increase very much with the increase in height.

TABLE 7.6 COMPARISON OF DISPLACEMENT OF COLUMN 1 FOR MODE 1 IN X DIR

Displacement for Column 1 (mm)							
Storey Level	Fixed base	Base Isolation (Bearings)					
		Lead Rubber		Friction Pendulum		High Damping Rubber	
		Basement	Base	Basement	Base	Basement	Base
0	0.00	-	26.01	-	26.29	-	25.97
1	1.24	-	26.31	-	26.52	-	26.28
2	1.90	26.64	26.37	26.34	26.56	26.57	26.34
3	9.43	27.32	26.81	26.81	26.88	27.28	26.80
4	19.92	27.96	27.34	27.28	27.26	27.95	27.36
5	30.21	28.50	27.79	27.67	27.58	28.51	27.82
6	37.63	28.85	28.08	27.93	27.80	28.88	28.13
7	41.72	29.04	28.24	28.06	27.92	29.07	28.29

Figure 7.10 shows the graphical representation of the displacement vs. storey level for column no 1 for mode 1 in X direction. From the graph we can see that the value of displacement for fixed base building varies as the height of the building increases, while for a base isolated building the value of displacement doesn't increase much with the increase in the height of the building.

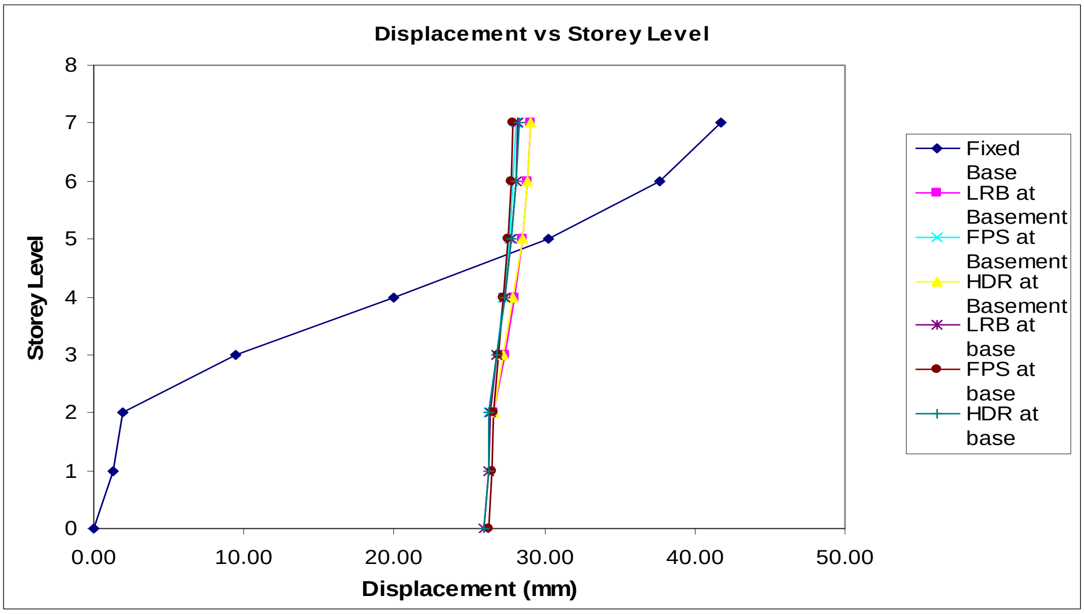


FIGURE 7.10 GRAPH OF DISPLACEMENT VS STOREY LEVEL FOR MODE 1 IN X DIR

Table 7.7 gives the comparison of displacement of column no 1 for mode 2 in Y direction for different storey levels. We can see that the displacement at the top of the building in case of fixed base building is 30 mm compared to 0 mm at the base level, while the increase in case of a base isolated building is very less for all the cases.

The displacement in bearings located at the base of the building is less than the bearings located at the base of the structure because of presence of rigid RC walls at in the first model.

TABLE 7.7 COMPARISON OF DISPLACEMENT OF COLUMN 1 FOR MODE 2 IN Y DIR

Displacement for Column 1 (mm)							
Storey Level	Fixed Base	Base Isolation (Bearings)					
		Lead Rubber		Friction Pendulum		High Damping Rubber	
		Basement	Base	Basement	Base	Basement	Base
0	0.00	-	17.02	-	17.23	-	16.94
1	0.90	-	17.24	-	17.46	-	17.16
2	1.54	17.77	17.29	17.89	17.51	17.72	17.22
3	9.03	18.40	17.69	18.53	17.93	18.37	17.63
4	16.03	18.82	18.04	18.95	18.30	18.80	17.99
5	22.77	19.19	18.36	19.33	18.63	19.19	18.32
6	27.70	19.44	18.58	19.58	18.86	19.45	18.55
7	30.57	19.59	18.70	19.72	18.99	19.60	18.69

Figure 7.11 shows the graphical representation of the displacement vs. storey level for column no 1 for mode 2 in Y direction. We can see that even in the Y direction value of displacement for fixed base building varies as the height of the building increases, while for a base isolated building the value of displacement doesn't increase much with the increase in the height of the building. Hence similar results are obtained as in X direction for building with isolators.

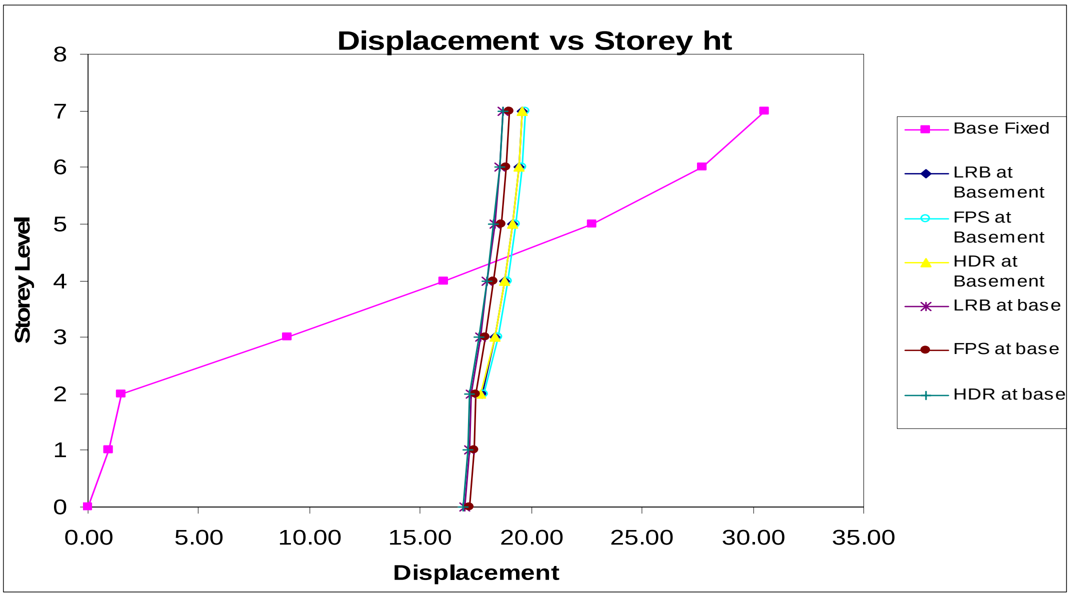


FIGURE 7.11 GRAPH OF DISPLACEMENT VS STOREY LEVEL FOR MODE 2 IN Y DIR

Table 7.8 gives the comparison of displacement of column no 1 for mode 3 i.e. torsion and the results of displacement has been plotted in Y direction for different storey levels. We can see that in the 3rd mode we are getting the maximum displacement at the base of the building by an amount of 30.61 in case of FPS located at the base of building. Allowable value is of 100 mm in case of FPS bearings which is much higher than obtained value.

TABLE 7.8 COMPARISON OF DISPLACEMENT OF COLUMN 1 FOR MODE 3 IN Y DIR

Displacement for Column 1 (mm)							
Storey Level	Fixed Base	Base Isolation (Bearings)					
		Lead Rubber		Friction Pendulum		High Damping Rubber	
		Basement	Base	Basement	Base	Basement	Base
0	0.00	-	29.00	-	30.61	-	29.00
1	1.63	-	29.30	-	30.70	-	29.32
2	2.36	33.13	29.36	34.70	30.73	33.08	29.37
3	15.03	34.03	29.93	34.96	30.91	34.03	29.97
4	28.17	34.67	30.41	35.13	31.06	34.70	30.47
5	39.94	35.19	30.79	35.26	31.17	35.24	30.87
6	48.17	35.53	31.05	35.36	31.25	35.59	31.14
7	52.41	35.71	31.19	35.40	31.29	35.78	31.28

FIGURE 7.12 gives the graphical presentation of displacement vs. displacement for column no 1 for mode 3.

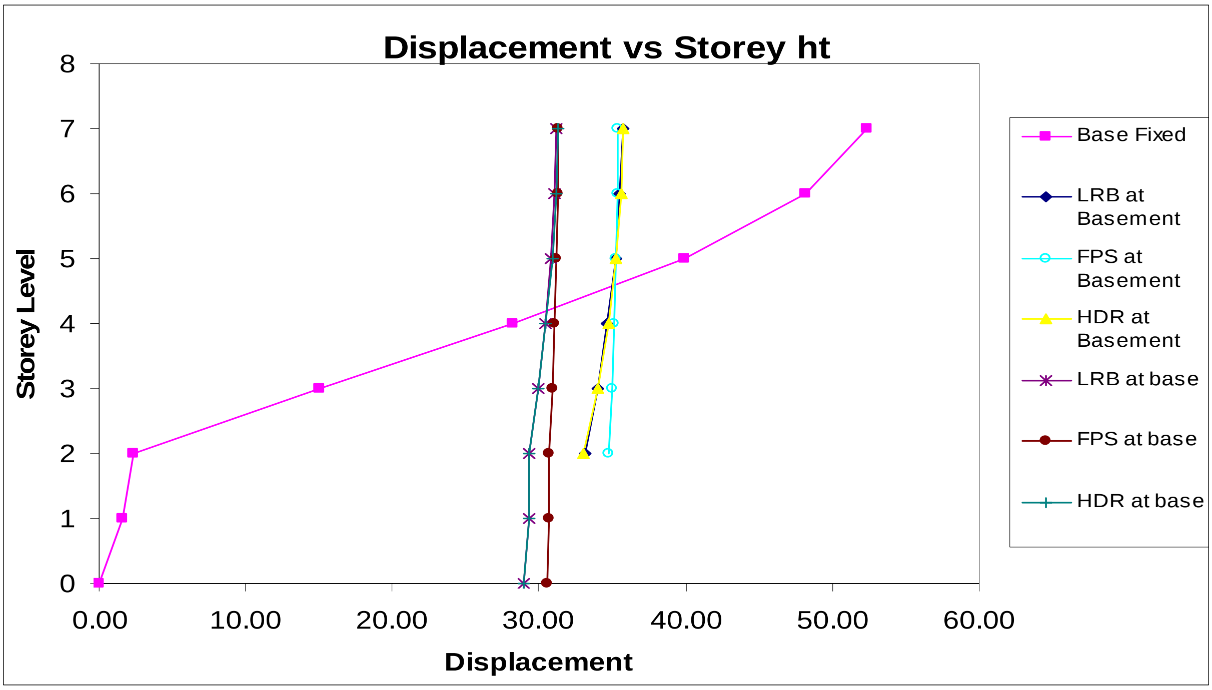


FIGURE 7.12 GRAPH OF DISPLACEMENT VS STOREY LEVEL FOR MODE 3 IN Y DIR

One of the main criteria for effective working of the base isolation is the reduction in the storey drift. This will directly reduce the storey acceleration and hence the damage is reduced.

Table 7.9 gives the comparison of storey drift vs. storey level of column no 1 for mode 1 in X direction. From the Table 7.9 we can see that storey drift is considerably reduced in case of base isolated building. We can see that LRB at basement gives very less values of storey drift compared to the fixed base building. The value of storey drift is checked according to IBC 2000 and is less than the permissible value.

TABLE 7.9 COMPARISON OF STOREY DRIFT OF COLUMN 1 FOR MODE 1 IN X DIR

Storey Level	Fixed base	Storey Drift for Column 1 (mm)					
		Base Isolation (Bearings)					
		Lead Rubber		Friction Pendulum		High Damping Rubber	
		Basement	Base	Basement	Base	Basement	Base
0	-	-	-	-	-	-	-
1	1.24	-	0.30	-	0.23	-	0.31
2	0.66	-	0.06	-	0.04	-	0.06
3	7.53	0.68	0.44	0.47	0.32	0.71	0.46
4	10.49	0.64	0.53	0.47	0.38	0.67	0.56
5	10.29	0.54	0.45	0.39	0.32	0.56	0.46
6	7.42	0.35	0.29	0.26	0.22	0.37	0.31
7	4.09	0.19	0.16	0.13	0.12	0.19	0.16

FIGURE 7.9 gives the graphical presentation of storey drift vs. Storey Level.

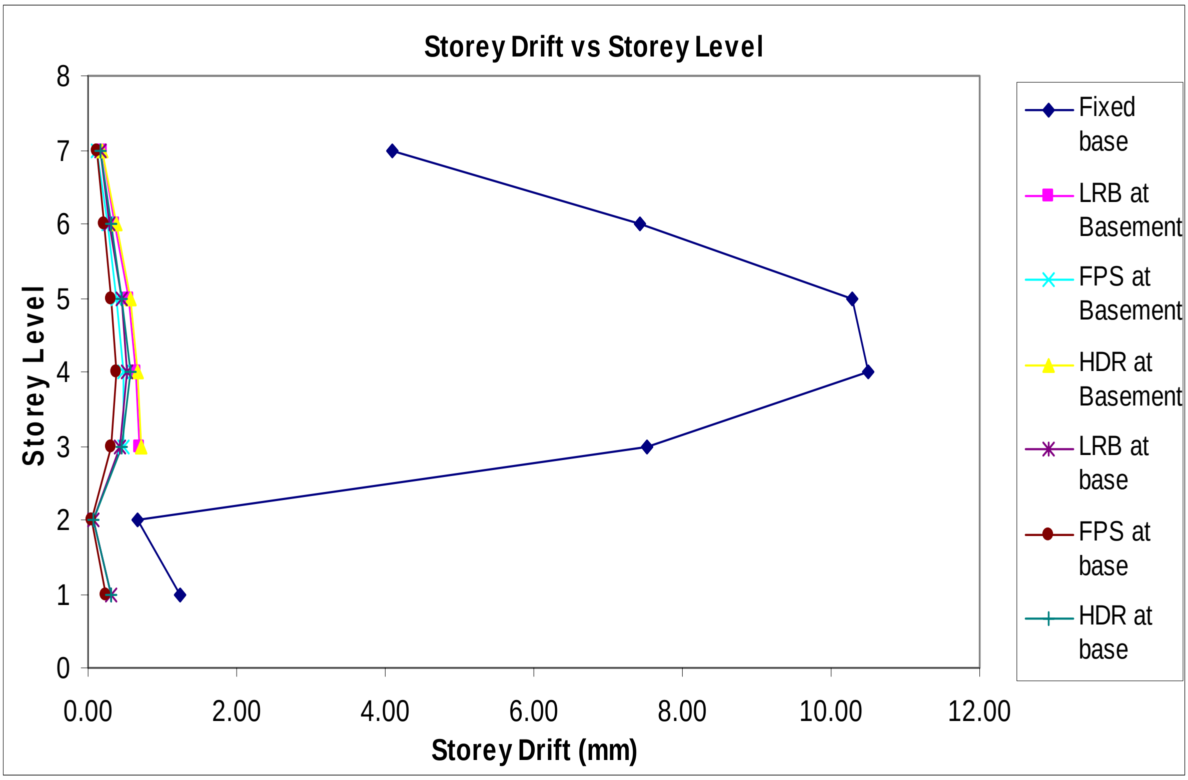


FIGURE 7.13 GRAPH OF STOREY DRIFT VS STOREY LEVEL FOR MODE 1 IN X DIR

Table 7.10 gives the comparison of storey drift vs. storey level of column no 1 for mode 2 in Y direction. From the Table 7.10 we can see that storey drift is considerably reduced in case of base isolated building. We can see that LRB at basement gives very less values of storey drift compared to the fixed base building. The value of storey drift is checked according to IBC 2000 and is less than the permissible value. Hence the storey drift is reduced and hence the third criterion for the effective working of the base isolation is achieved here.

TABLE 7.10 COMPARISON OF STOREY DRIFT OF COLUMN 1 FOR MODE 2 IN Y DIR

Storey Drift for Column 1 (mm)							
Storey Level	**Fixed base**	**Base Isolation (Bearings)**					
		Lead Rubber		**Friction Pendulum**		**High Damping Rubber**	
		Basement	**Base**	**Basement**	**Base**	**Basement**	**Base**
0	-	-	-	-	-	-	-
1	0.90	-	0.22	-	0.23	-	0.22
2	0.64	-	0.05	-	0.05	-	0.06
3	7.49	0.63	0.40	0.64	0.42	0.65	0.41
4	7.00	0.42	0.35	0.42	0.37	0.43	0.36
5	6.74	0.37	0.32	0.38	0.33	0.39	0.33
6	4.93	0.25	0.22	0.25	0.23	0.26	0.23
7	2.87	0.15	0.12	0.14	0.13	0.15	0.14

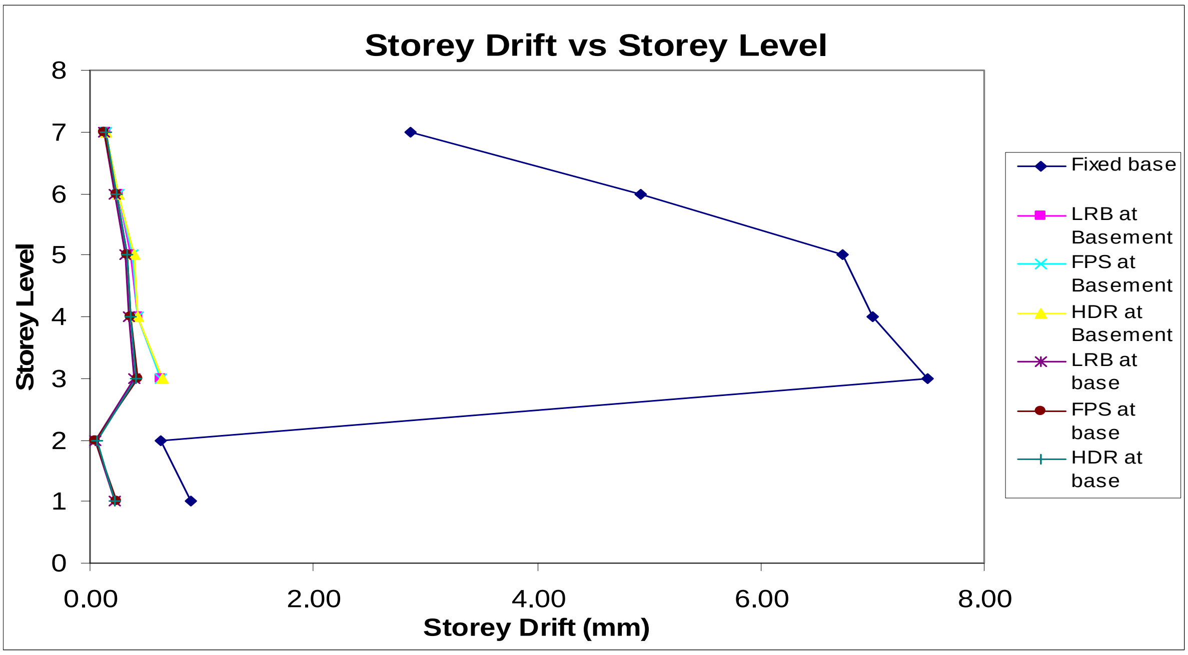


FIGURE 7.14 GRAPH OF STOREY DRIFT VS STOREY LEVEL FOR MODE 2 IN Y DIR

TABLE 7.11 COMPARISON OF STOREY DRIFT OF COLUMN 1 FOR MODE 3 IN Y DIR

Storey Drift for Column 1 (mm)							
Storey Level	**Fixed base**	**Base Isolation (Bearings)**					
		Lead Rubber		**Friction Pendulum**		**High Damping Rubber**	
		Basement	**Base**	**Basement**	**Base**	**Basement**	**Base**
0	-	-	-	-	-	-	-
1	1.63	-	0.30	-	0.09	-	0.32
2	0.73	-	0.06	-	0.03	-	0.05
3	12.67	0.90	0.57	0.26	0.18	0.95	0.60
4	13.14	0.64	0.48	0.17	0.15	0.67	0.50
5	11.77	0.52	0.38	0.13	0.11	0.54	0.40
6	8.23	0.34	0.26	0.10	0.08	0.35	0.27
7	4.24	0.18	0.14	0.04	0.04	0.19	0.14

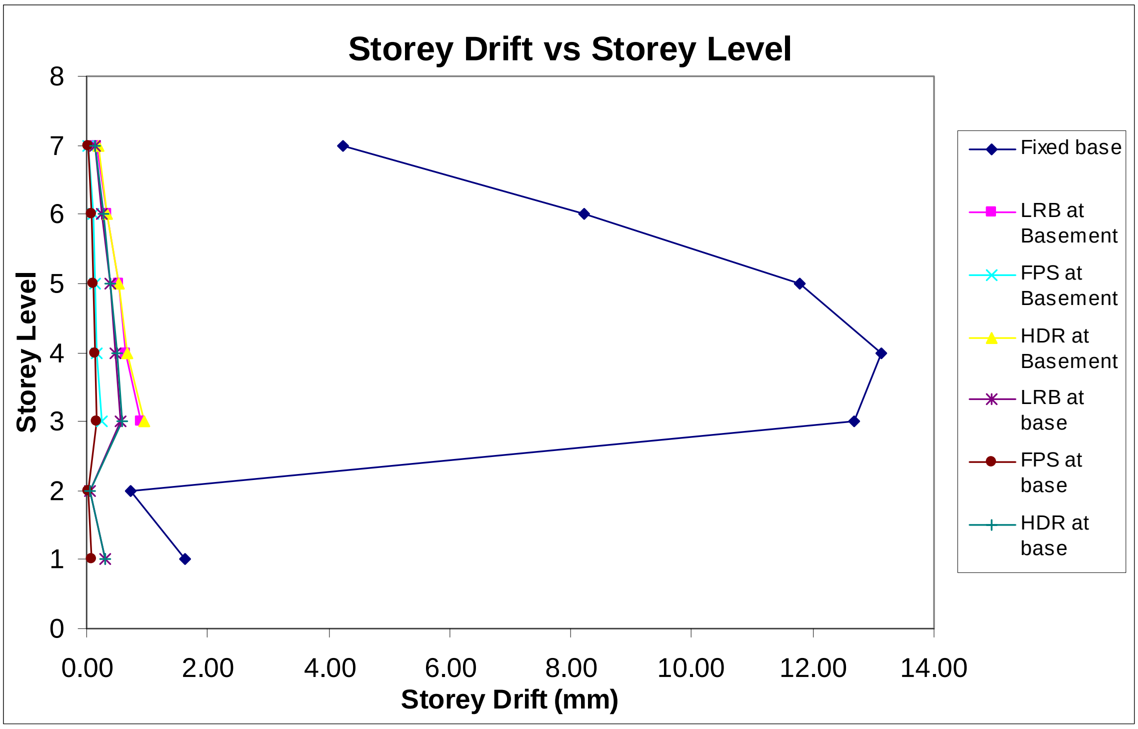


FIGURE 7.15 GRAPH OF STOREY DRIFT VS STOREY LEVEL FOR MODE 3 IN Y DIR

8. CONCLUSIONS AND FUTURE SCOPE OF WORK

8.1 CONCLUSIONS

The primary aim of this work is to develop a 3D model that accounts for the essential dynamic behavior of a base-isolated building and allows predictions to be made of the isolation performance against ground-borne vibration. To achieve this aim, a number of specific objectives were set, as given in Section 1.3. These are now reviewed and consideration is given to the extent to which they have been met.

A 3D frame was modeled using SAP2000 with fixed base and base-isolated conditions. From the results presented in Chapter 7, the following conclusions have been drawn.

After detailed study of work, following conclusions were made.

- The fundamental time period of base isolated structure is increased by almost 4 times as compared to that of a fixed base building.
- The base shear in X direction for Lead rubber bearings located at the top of the basement column was reduced by 66 %.
- The base shear in X direction for High damping rubber bearings located at the top of the basement column was reduced by 65 %.
- The base shear in X direction for Friction pendulum system located at the top of the basement column was reduced by 65 %.
- Displacement obtained at the base of the building in mode 1 for LRB located at the base is 26.01 mm, while no displacement was obtained at the base in fixed condition.
- Displacement obtained at the base of the building in mode 1 for HDR located at the base is 25.97 mm, while no displacement was obtained at the base in fixed condition.
- Displacement obtained at the base of the building in mode 1 for FPS located at the base is 26.29 mm, while no displacement was obtained at the base in fixed condition.
- Storey drift at the 4^{th} level in mode 1 for LRB located at the base of the building was reduced to 0.53 mm from 10.49 mm.

Thus, Base isolation achieves the reduction in earthquake forces along with shift in the modal time period and decrease in the storey drift.

FURTHER SCOPE OF WORK:

Looking to the work done in present thesis following work can be taken as future scope of work related to this topic.

- Check the optimum size & shape of bearing required for isolation of structure.
- Determination of most feasible locations of base isolators.
- Design & feasibility constraints of isolator system.
- Innovative methods of isolation of structure with ground motion.
- Cost optimization of bearings.
- Parametric study of damping of bearings used for isolation.

EXCEL SPREADSHEET FOR DESIGN OF BEARINGS

The design of Lead rubber bearings, High Damping Rubber bearings & Friction Pendulum Systems is a challenging task and is carried out by trial and error method. The design was carried out according to IBC 2000 guidelines and to support the calculations a generalized program was prepared in Microsoft Excel sheet. The design of the bearings is given in chapter 5 with detailed calculations and equations. Here the input for design, calculation carried out & output of the design is given below as carried out in the Excel sheet. The various necessary checks are also given here.

I. DESIGN OF LEAD RUBBER BEARINGS

INPUT

Service Load = W =	2600	kN	
Total Weight = W_T =	30238	kN	
Max. Load due to EQ, $P_{DL+LL+EQ}$ =	2225	kN	
Gravitational Acceleration, g =	9.81	m/s^2	
Yield Strength of Lead Core, F_{py} =	8.82	MN/m^2	
Rubber Hardness =	IRHD 70		
Young's Modulus, E =	735	N/cm^2	
Shear Modulus, G =	173	N/cm^2	
Modified Factor, k =	0.53		
Elongation at break =	500	%	5
Assumed Length of Bearing =	0.25		
			OK
Assumed Width of Bearing =	0.55	m	
Assume Cover plates =	2.5	cm	
Width of building in plan in X dir, b =	22.98	m	
Width of building in plan in Y dir, d =	16.04	m	

DESIGN CALCULATIONS

Assumptions made for the design

Target Period, T_D =	2.5	sec	
Maximum Shear Strain, r_{max} =	50	%	0.5
Effective Damping Ratio, E_{eff} =	10	%	0.1
Damping Coefficient, B_D =	1.2		
Seismic Coefficient, S_D =	0.4		

Analysis

Effective horizontal stiffness K_{eff} of Isolator is =	1672.41	kN/m
	1.67	MN/m
Design Displacement, D_D =	0.21	m
	0.21	m

Design of bearing

Determine the isolator size

Total Rubber Height, t_r =	0.42	m
	0.42	m
Short term yield force Q_d =	55.17	kN
	55.17	kN
The Post Yeild Horizontal Stiffness, K_d =	1409.70	kN
	1409.7	kN

Design of Lead core

Required Lead Area, A_p =	0.006	m^2
	62.55	cm^2
	62.55	cm^2
Diameter of Lead core =	8.92	cm
	9	cm

Rubber properties

Rubber Hardness =	IRHD 70		
Young's Modulus = E =	735	N/cm^2	
Shear Modulus = G =	173	N/cm^2	
Modified Factor = k =	0.53		
Elongation at break = ε_b =	500	%	5

Determine area A & thickness t of individual rubber layers

Select shape factor S

S >	9.37		10
E_c =	78645	N/cm^2	
Use E_c =	786.45	MN/m^2	

Determine the effective area A_0 for the bearing based on allowable axial stress σ_c for the vertical load case

σ_c =	W/A_0	> 7.84	MN/m^2
A_0 >	0.33	m^2	
Use A_0 =	0.33	m^2	

Determine the effective area A_1 of the bearing from the shear strain condition for the vertical load

A_1 >	0.12	m^2
Use A_1 =	0.12	m^2

Determine the elastic stiffness K_r of the bearing

K_r =	1149.52	kN/m

Obtain the minimum area A_{sf} for the shear failure of the bearing

A_{sf} =	0.28	m^2
	0.28	m^2
Assume width b =	0.55	m
So, length of the bearing, L =	0.25	m

A_2 = 0.09 m^2

Design cross-sectional area of the bearing

A = max(A_0, A_1, A_2) = 0.33 m^2

Determine the size of rubber layers

Assume Width of Bearing, B = 0.55 m

Assume Length of Bearing, L = 0.25 m

So, Reduced Area = A_{re} = 0.09 m^2

Determine single layer thickness t & number of layers N for a rectangular bearing

t = 0.86 cm

N = 48.87

Use N = 50

Determine the steel plate thickness, t_s

t_s = 0.01 m

So, t_s = 6.39 mm

$t_s \geq$ 2 mm (In any condition)

Hence, Use t_s = 6.39 mm

Total height h of the bearing

h = 789.32 mm

So, h = 78.93 cm

Check for shear strain under vertical load

$\gamma_c \leq$ 1.67 (In any condition)

γ_c = 0.60

Hence, the Design is, **SAFE**

Check for stability under vertical load

$\sigma_c \leq$	9061.90	kN/m^2	(In any condition)
$\sigma_c =$	7840	kN/m^2	
Hence, the Design is		**SAFE**	

Check for diameter of lead core

1.25	$\leq H_p/d_p \leq$	5	(In any condition)
H_p/d_p =	4.67		
Hence, take H_p/d_p =		4.67	
Diameter of Lead Core =		10	cm

Check on stability & roll-out conditions under earthquake load

1. Shear strain condition for earthquake load

$P_{DL+LL+EQ}$ =	2225.01	kN
	2.22501	MN

Strain due to compression, γ_{sc} =		0.606
Strain due to Earthquake, γ_{eq} =		0.5
So, θ =	0.0036867	
Strain due to rotation, γ_{sr} =		0.154
$\gamma_{sc} + \gamma_{eq} + \gamma_{sr}$ =	1.26074	
$0.75\varepsilon_b$ =	3.75	
Hence, the design is,	**SAFE**	

2. Roll-out condition

$\delta_{roll\text{-}out}$ =	0.2267955	m
	226.79552	mm
D_D =	210	mm
Hence, the design is,	**SAFE**	

DESIGN RESULTS (All dimensions are in mm)	
Width of bearing, B	550
Length of bearing, L	250
Diameter of Lead Core	100
Total height of bearing, h	789
Number of rubber layers, N	50
Thickness of individual rubber layers, t	8.6
Number of steel plates, N_s	50
Thickness of individual steel plates, t_s	6.4
Thickness of top and bottom cover plates	250

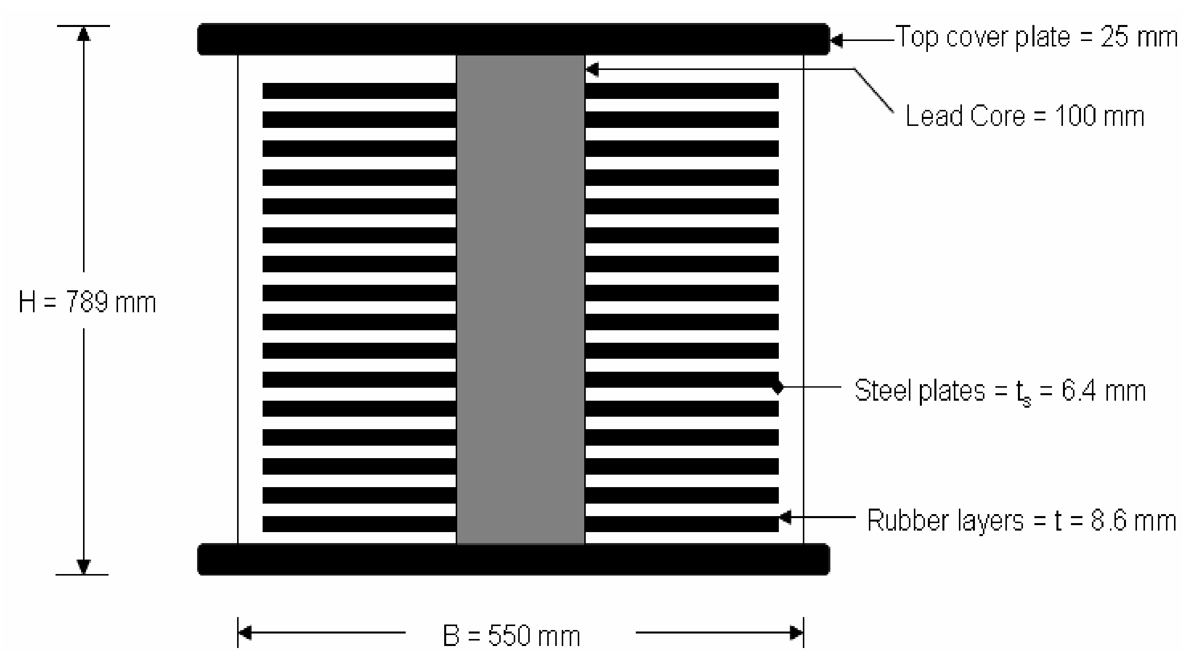


FIGURE A.1 DIMENSIONS OF LRB

II. DESIGN OF HIGH DAMPING RUBBER BEARING

INPUT

R_I =	2		
Service Load = W =	2600	kN	
Total Weight = W_T =	30238	kN	
Max. Load due to EQ, $P_{DL+LL+EQ}$ =	2225	kN	
Gravitational Acceleration, g =	9.81	m/s^2	
Rubber Hardness =	IRHD 60		
Young's Modulus, E =	445	N/cm^2	
Shear Modulus, G =	106	N/cm^2	
Modified Factor, k =	0.57		
Elongation at break =	500	%	5
Assumed Length of Bearing, L =	0.25	m	OK
Assumed Width of Bearing, B =	0.55	m	
Assume Cover plates =	2.5	cm	
No of columns =	26		
Width of building in plan in X dir, b =	22.982	m	
Width of building in plan in Y dir, d =	16.04	m	

DESIGN CALCULATIONS

Assumptions made for the design

Target Period, T_D =	2.5	sec	
Maximum Shear Strain, r_{max} =	150	%	1.5
Effective Damping Ratio, E_{eff} =	20	%	
Damping Coefficient, B_D =	1.5		
Seismic Coefficient, S_D =	0.4		

Analysis

Effective horizontal stiffness K_{eff} of Isolator is =	1674.11	kN/m
	1.67	MN/m
Design Displacement, D_D =	0.17	m

			0.17	m

Design of bearing

Determine the isolator size

Total Rubber Height, t_r =	0.11	m
So, Use t_r =	0.12	m

Rubber properties

Rubber Hardness =	IRHD 60		
Young's Modulus = E =	445	N/cm^2	
Shear Modulus = G =	106	N/cm^2	
Modified Factor = k =	0.57		
Elongation at break = ε_b =	500	%	5

Determine area A & thickness t of individual rubber layers

Select shape factor S

S >	9.09		10
E_c =	51175	N/cm^2	
Use E_c =	511.75	MN/m^2	

Determine effective area A_0 of the bearing based on allowable axial stress σ_c for the vertical load case

σ_c =	W/Ao	> 7.84	MN/m^2
A_0 >	0.33	m^2	
	0.33	m^2	

Determine the effective area A_1 of the bearing from the shear strain condition for the vertical load

A_1 >	0.18	m^2
Use A_1 =	0.18	m^2

Obtain the minimum area A_{sf} for the shear failure of the bearing

A_{sf} = 0.19 m^2

A_2 = 0.10 m^2

Design cross-sectional area of the bearing

A = max(A_0, A_1, A_2) = 0.33 m^2

Determine the size of rubber layers

Assume Width of Bearing, B = 0.55 m

Assume Length of Bearing, L = 0.25 m

So, Reduced Area = A_{re} = 0.14 m^2

Determine single layer thickness t & number of layers N for a rectangular bearing

T = 0.86 cm

N = 13.96

Use N = 14

Determine the steel plate thickness, t_s

t_s = 0.006 mm

So, t_s = 5.71 mm

$t_s \geq$ 2 mm (In any condition)

Hence, Use t_s = 5.71 mm

Total height h of the bearing

H = 250.00 mm

So, h = 25.00 cm

Check for shear strain under vertical load

$\gamma_c \leq$ 1.67 (In any condition)

γ_c = 0.92

Hence, the Design is, SAFE

Check for stability under vertical load

$\sigma_c \leq$ 8833.33 KN/m^2 (In any condition)

$\sigma_c =$ 7840 KN/m^2

Hence, the Design is SAFE

Check on stability & roll-out conditions under earthquake load

1. Shear strain condition for earthquake load

$P_{DL+LL+EQ} =$ 2225.01 kN

2.22501 MN

Strain due to compression, $\gamma_{sc} =$ 1.3765

Strain due to Earthquake, $\gamma_{eq} =$ 1.4167

So, $\theta =$ 0.002984

Strain due to rotation, $\gamma_{sr} =$ 0.4377

$\gamma_{sc} + \gamma_{eq} + \gamma_{sr} =$ 3.230856

$0.75\varepsilon_b =$ 3.75

Hence, the design is, **SAFE**

2. Roll-out condition

$\delta_{roll\text{-}out} =$ 0.231462 m

231.4619 mm

$D_D =$ 170.00 mm

Hence, the design is, **SAFE**

DESIGN RESULTS (All dimensions are in mm)	
Width of bearing, B	550
Length of bearing, L	250
Total height of bearing, h	250
Number of rubber layers, N	14
Thickness of individual rubber layers, t	8.6
Number of steel plates, N_s	14
Thickness of individual steel plates, t_s	5.7
Thickness of top and bottom cover plates	25

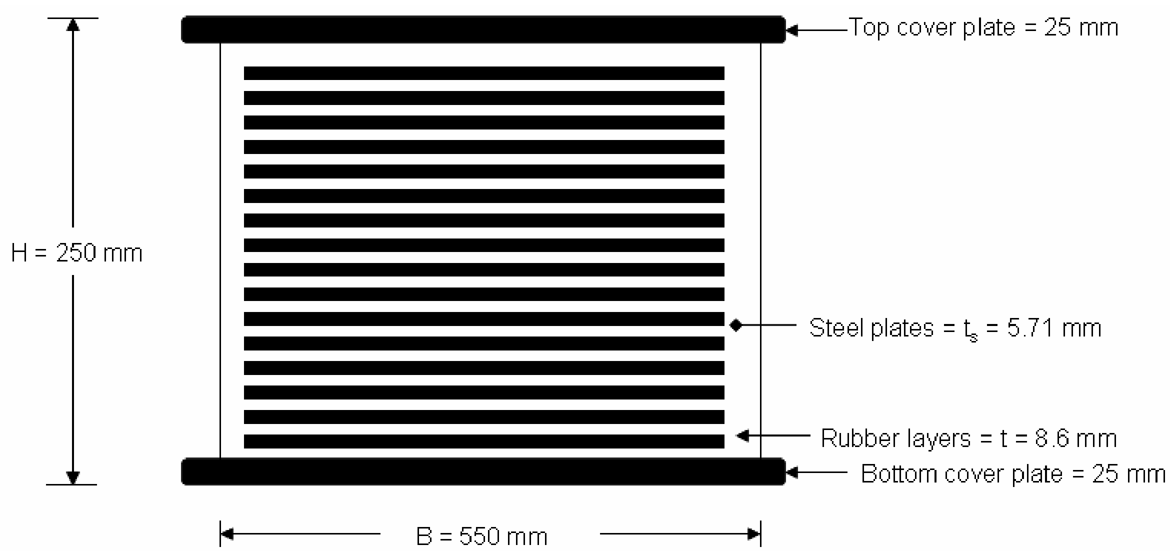


FIGURE A.2 DIMENSIONS OF HIGH DAMPING RUBBER BEARING

III. DESIGN OF FRICTION PENDULUM SYSTEM

INPUT

Service Load = W =	2600	kN	
Total Weight = W_T =	30238	kN	
Gravitational Acceleration, g =	9.81	m/s^2	
Assume Cover plates =	5.0	cm	
Depth of disk, δ =	1.7	cm	OK
Use diameter, d =	25	cm	OK

DESIGN CALCULATIONS

Assumptions made for the design

Target Period, T_D =	2.5	sec	
Friction Coeff. of Spherical Surface, μ =	0.06		
Design horizontal displacement, D_D =	12	cm	
Effective Damping Ratio, E_{eff} =	20	%	0.2
Damping Coefficient, B_D =	1.5		
Seismic Coefficient, S_D =	0.2		

Determine the size of FPS

Radius of Curvature of Spherical Sliding Surface of Isolation,

R_{fps} = 1.55 m

1.6 m

Determine the total effective stiffness of the isolation system

ΣK_{eff} = 34018.31 KN/m

Avg Effective Stiffness for a Single FPS Isolator = 17009.15 kN/m

Determine the effective damping ξ_{eff} for FPS

ξ_{eff} = 0.28

28.29 %

Check the design displacement D_D

$D_D <$	0.12	m	(In any condition)
$D_D =$	0.08	m	
	0.09	m	

Hence the design displacement is, SAFE

Estimate the vertical displacement δ_v

$\delta_v =$	0.005	m
	0.45	cm

Use, depth δ =	1.7	cm	Safe
Use, diameter d =	25	cm	Safe

Check for vertical displacement, δ_v

$\delta_v >$	0.005	m	(In any condition)
$\delta_v =$	0.005	m	
	0.005	m	

Hence the vertical displacement is, SAFE

Check on the recentering condition for the earthquake load case

$\mu >$	0.06	(In any condition)
$\mu =$	0.08	

Hence the design is, SAFE

DESIGN RESULTS (All dimensions are in mm)	
Radius of Curvature of spherical surface, R_{fps}	1600
Depth of the disk, δ	17
Diameter of disk, d	250

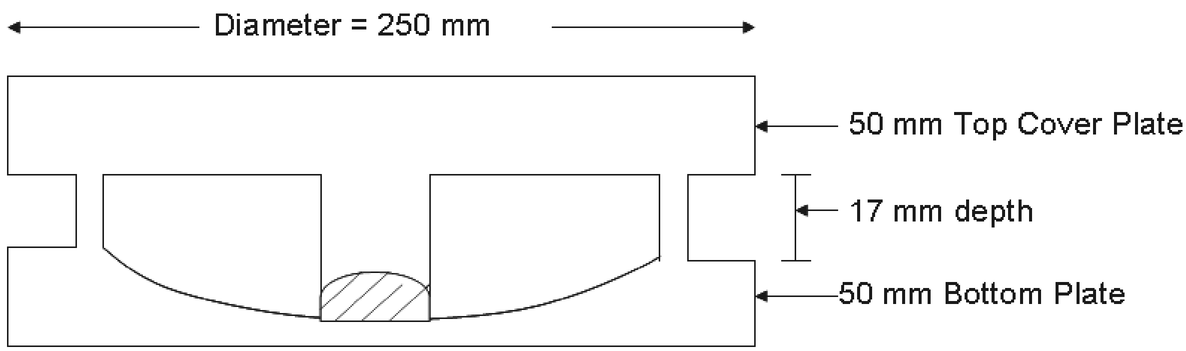


FIGURE A.3 DIMENSIONS OF FPS

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