A NEW HYBRID COMPOSITE ISOLATION SYSTEM FOR EARTHQUAKE PROTECTION OF STRUCTURES

2019
Ph. D. THESIS
METALLURGICAL AND MATERIALS ENGINEERING

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A NEW HYBRID COMPOSITE ISOLATION SYSTEM FOR EARTHQUAKE PROTECTION OF STRUCTURES

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES OF
KARABUK UNIVERSITY

BY

SALAH MUSTAFA A. ALMUSBAHI

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR
THE DEGREE OF Ph.D. SCIENCE IN
DEPARTMENT OF
METALLURGICAL AND MATERIALS ENGINEERING

February 2019

I certify that in my opinion the thesis submitted by Salah Mustafa A. ALMUSBAHI titled "A NEW HYBRID COMPOSITE ISOLATION SYSTEM FOR EARTHQUAKE PROTECTION OF STRUCTURES" is fully adequate in scope and quality as a thesis for the degree of Doctor of Philosophy.

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The degree of Doctor of Philosophy by the thesis submitted is approved by the Administrative Board of the Graduate School Natural and Applied Sciences, Karabük University.

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"I declare that all the information within this thesis has been gathered and presented in accordance with academic regulations and ethical principles and I have according to the requirements of these regulations and principles cited all those which do not originate in this work as well."

Salah Mustafa A. ALMUSBAHI

ABSTRACT

Ph. D. Thesis

A NEW HYBRID COMPOSITE ISOLATION SYSTEM FOR EARTHQUAKE PROTECTION OF STRUCTURES

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February 2019, 119 pages

Seismically resistant safe structures can be ordered into inflexible structures and adaptable structures. In rigid structures, the control methods that are connected to withstand great pressures decrease inner storey displacement with the assistance of corner-to-corner popping, the establishment of shear walls and the utilization of composite materials. In flexible structures, such as in base-isolated structures, the key control methodology is to decrease the increasing excitation with the utilization of dampers and isolators.

The main point of this thesis is to introduce and model a new hybrid composite isolation system for the protection of structures against earthquakes. This system is utilized in a supporting base and is mainly based on a simulation in computer software called ANSYS. It is implemented to determine the dynamic response of the structure. A 40-storey building with multiple degrees of freedom was studied under seismic waves.

In this study, our 40-storey structure has been retrofitted with the proposed hybrid isolation system and analyzed. The building's width and height are respectively 40 meters and 160 meters. In addition, the stiffness wass supposed to be linearly distributed. The building has been studied under two different boundary conditions. In the first case, the base of the building is rigidly attached to the ground, and in the second, it is retrofitted with the proposed hybrid isolation system.

The results show a noticeable reduction in displacement, velocity and acceleration of the building floors. The isolated case can be preferred for the structure to prevent it from experiencing severe damage. Thus, this model can be considered as new hybrid composite isolation systems for the protection of structures from catastrophic earthquake damages.

Keywords **:** Isolation system, hybrid composite, structural analysis, seismic wave.
Science Code: 915.1.092

ÖZET

Doktora Tezi

YAPILARIN DEPREMDEN KORUMAK İÇİN YENİ BİR HİBRİT KOMPOZİT İZOLASYON SİSTEMİ

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Prof. Dr. Ali GÜNGÖR

Şubat 2019, 119 sayfa

Sismik olarak dayanıklı güvenli yapılar, esnek olmayan yapılar ve uyarlanabilir yapılar olarak sıralanabilir. Rijit yapılarda, büyük basınçlara dayanacak olan kontrol yöntemleri, köşeden köşeye çıkma, perde duvarlarının oluşturulması ve kompozit malzemelerin kullanımı ile iç kat yer değiştirmesini azaltır. Taban yalıtımlı yapılar gibi esnek yapılarda, temel kontrol metodolojisi, darbe emici ve ayırıcıların kullanımı ile artan uyarımı azaltmaktır.

Bu tezin temel amacı, yapıların depremlere karşı korunması için yeni bir karma kompozit izolasyon sistemi tanıtmak ve modellemektir. Bu sistem destekleyici bir tabanda kullanılmaktadır ve temel olarak ANSYS adlı bir bilgisayar yazılımı simülasyonuna dayanmaktadır. Yapının dinamik tepkisini belirlemek için uygulanır. Sismik dalgalar altında çoklu serbestlik dereceli 40 katlı bir bina incelenmiştir.

Bu çalışmada, 40 katlı yapımız önerilen hibrit izolasyon sistemi ile güçlendirilmiş ve analiz edilmiştir. Binanın eni ve yüksekliği sırasıyla 40 ve 160 metredir. Ek olarak, sertliğin doğrusal olarak dağıldığı farz edilmiştir. Bina iki farklı sınır şartında incelenmiştir. İlk durumda, binanın tabanı sağlam bir şekilde zemine tutturulmuştur ve ikincisinde önerilen hibrit izolasyon sistemi ile güçlendirilmiştir.

Sonuçlar, bina zeminlerinin yer değiştirme, hız ve ivmelenmesinde gözle görülür bir azalma olduğunu göstermiştir. İzole durum, yapının ciddi hasar görmesini önlemek için tercih edilebilir. Dolayısıyla, bu model, yapıların yıkıcı deprem hasarlarından korunmasına yönelik yeni hibrid kompozit izolasyon sistemleri olarak düşünülebilir.

Anahtar Kelimeler: İzolasyon sistemi, hibrit kompozit, yapısal analiz, sismik dalga.
Bilim Kodu **:** 915.1.092

ACKNOWLEDGMENTS

First of all, I would like to express deepest gratitude to my supervisor Prof. Dr. Ali GÜNGÖR for his grateful motivation, guidance, support, continuous advice and constructive suggestions toward the completion of this thesis.

I would like to acknowledge my committee for their contributions in time and advice to improve this work.

To my mother, I appreciate her for encouraging me to bring passion and love to whatever endeavor I undertake. She has been there since the beginning, supportingme throughout my degree programs, and even stayed with me to ensure the completion of this thesis, I am lucky to have such a wonderful family.

I would like to thank my family and my wife for their support, encouragement and patience throughout my studies.

If I overlooked anyone, please accept my apologies, since there are so many nice and kind people, who provided me with moral support throughout this endeavor.

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LIST OF SYMBOLS AND ABBREVIATIONS

ABWR	: Advanced Boiling Water Reactor.
AIUF	: Additional Isolated Upper Floor.
AM	: ANSYS Mechanical.
AREBS	: Advantages of Steel Re-inforced Elastomeric Bearings.
BIB	: Base-Isolated Buildings.
BRB	: Buckling Restrained Braces.
CAD	: Computer Aided Design.
EB	: Elastomeric Bearing.
FBI	: Full Base Isolation.
FD	: Fluid Dampers.
FPS	: Friction Pendulum System.
FSB	: Flat Slider Bearing.
FVED	: Friction-Viscous-Elastic Damper.
HDRB	: High Damage Rubber Bearing.
HIS	: Hybrid Isolation System.
HSB	: Horizontal Sliding Bearings.
IUS	: Isolated Upper Slabs.
LRB	: Lateral Elasticity Function.
LPRB	: Lead-Plug Rubber Bearings.
LRB	: Lead-Rubber Bearings.
LRB	: Laminated Rubber Bearing.
MIS	: Mixed Isolation systems.
MLEB	: Multi-Layered Elastomeric Bearings.
MR	: Magneto-Rheological.
SDBPS	: Static-Dynamic Interchangeable Ball Pendulum System.
SDOF	: Single Degree of Freedom.
SI	: Seismic Isolation.
TELCE	: Taft and El Centro Earthquakes.

TFPS	: Trajectory Friction Pendulum Systems.
TMD	: Turned Mass Damper.

PART 1

INTRODUCTION

1.1. BACKGROUND

Earthquakes are a natural occurrence and have been occurring for over a billion years on our planet. By definition, an earthquake is an unexpected/immediate earth shaking due to the rock underneath the Earth expelling stored energy. Earthquakes occur when the Earth’s upper surface moves and two of its blocks slip. The slipped surface is termed a fault plane. In the past, very little was known about what lies beneath the Earth’s surface. However, experts now have more knowledge than ever before. In fact, the place underneath, which is the center of an earthquake, is termed the hypocenter and the place above it is termed the epicenter.

When an earthquake occurs, a number of aftershocks/foreshocks are also observed, which are actually low intensity earthquakes, and they occur after a major or high-intensity earthquake. The first and high-intensity earthquake is termed the “main shock”. Experts believe that main shocks almost always have aftershocks which occur in the same geographical location as the first shock. Sometimes, aftershocks continue for long time after a main shock. Earthquakes have affected most geographical locations on Earth, some of which were sometimes mild and sometimes quite catastrophic. Earthquakes have destroyed property and have taken lives.

Stronger earthquakes violently shake the surface, which is detrimental to life. Sometimes, a strong earthquake shakes buildings to such an extent that they move down the Earth. Scientists and explorers have discovered many buried cities which appeared to have been developed civilizations and fell deep into the Earth mainly because both rocky structures and the soil fel at a high speed. An earthquake can intensify a landslide which buries buildings while people are still in them. Every year, many governments in addition to vulnerable communities make efforts and invest huge sums of money on warnings and the mitigation of disasters caused by earthquakes.

Earth comprises four important layers, namely the mantle, the inner core, the outer core and the crust which lies above the mantle. The ground surface is actually a thin skin that is divided into several parts all of which cover the Earth's surface. Beneath the Earth's surface, there are a number of pieces of land which are quite puzzling and actually move very slowly. Sometimes, they collide with each other and release a great amount of energy. These pieces are termed tectonic plates. One of their important features is their edges, termed plate boundaries. These boundaries have a number of irregularities called faults. These faults are the reason for the majority of earthquakes. Experts believe that their edges are roughened and become entangled with each other and the remaining plate moves. The plate has power and structure to move the edges, so when it pulls the edge, people living on the surface experience earthquakes.

Experts have categorized earthquakes into three based on the fact that there are three types of plate boundary, including spreading ridges, convergent boundaries and transformational boundaries. Their descriptions are given in the following chapters.
If we take the case of Turkey, it has suffered terrible earthquakes throughout its history. Some of its areas are located in Asia and some in Europe. Moreover, it has geographical contact with Africa. Scientists believe that the North Anatolian fault line is the world's most dangerous seismic line, which has so far resulted in two of the most devastating earthquakes in the country's history. In recent history, 32000 people were lost in 1939, when a devastating earthquake occurred in Erzincan, and again in 1999 in Marmara. Both earthquakes caused massive loss of life, economy and property. In 1999, 17000 people died and another 50000 were injured when the earthquake hit 120000 housing units. Many people became temporarily homeless. In other less devastating earthquakes by 2010, 20000 had also died.

The country lost 5 percent of its GDP to earthquakes, which has varied between $8 billion and $30 billion on different occasions. Earthquakes partially or completely damage a number of important industries, which adversely affects the overall economy. A summary of important earthquake information is presented in Table 1.1.

Table 1.1. Major earthquakes in Turkey.

Earthquake (Date, City, Region)	Magnitude	Fatalities
1939 12 26, Erzincan, East	7.8	32700
1942 12 20, Tokat, Central	7.6	4000
1943 11 26, Samsun, North	7.6	4000
1944 02 01, Bolu, Northwest	7.4	2790
1953 03 18, Balikesir, West	7.3	1073
1966 08 19, Mus, East	6.8	1529
1970 03 28, Izmir, West	6.9	1086
1975 09 06, Diyarbakir, Southeast	6.7	2000
1983 10 30, Erzurum, East	6.9	1342
1999 08 17, Izmir, Northwest	7.4	17118
1999 11 12, Duzce, Northwest	7.2	894
2003 05 01, Bingol, East	6.4	177
2010 03 08, Bingol, East	6.1	51

1.2. PROTECTION FROM EARTHQUAKES

Protecting against earthquakes has been a topic of interest for many decades in almost every country. Fortunately, the research on this topic started long ago. Experts have presented a number of effective ways to protect against and reduce earthquake damage some of which have obviously been orthodox while others have been non-traditional.

The first and the foremost method is based on structural brute force, which implies that a construction should be sufficiently strong and tough to resist earthquakes. However, it is not cost-effective as the structure needs to be sufficiently strong to resist seismic movement.

A novel approach to earthquake resistance is called base isolation, which resolves the problems with traditional techniques. Base isolation mitigates earthquake disasters, so it has been a priority solution for a few decades. Base isolation includes support mechanisms that disconnect a building from ground movement and prevents seismic acceleration from reaching a building or slows it. If we separate a building from the surface of the ground at the time of an earthquake, the structure moves very little as compared to the ground. Base isolation possesses force-displacement properties that are very flexible and have considerably high damping and force absorption limits, which causes considerable stiffness in a structure [1].

Base isolation is useful when it has some dependable building parameters that successfully isolate the base from violent surface motion. Therefore, it requires a thorough understanding of the needed parameters in addition to the support systems available to deal with extraordinary seismic movement. Whenever a support system is less stiff, it will perform better during a seismic emergency and its effectiveness will be maintained over a long period as it lowers the seismic inertia on a building.
Many base-isolating devices are available to isolate a structure during an earthquake. This function can be performed with laminated elastomeric rubber bearings, yielding steel devices, lead rubber bearings, lead extrusion devices and friction devices (PTFE) sliding bearings.

1.3. VIBRATION

Vibration isolation is a very helpful method to reduce or mitigate the earthquake intensity for a particular structure and a resulting disaster. It controls vibration by changing the transmission path between a vibrating building and the excitation source. This occurs through specially designed structural elements known as vibration isolation systems. In fact, transmissibility is a ratio between isolating system displacement and its input displacement. This ratio provides a clear picture about the optional effectiveness of any vibration isolation system. These isolation systems might amplify an earthquake rather than isolate the foundation. As far as passive systems are concerned, they do not create isolation at certain frequencies, which are lower than the system resonance. In such cases, ground vibrations directly transfer through the isolation system [2]. It can also be explained by the fact that amplification occurs at a certain resonance, which means that the transmissibility is more than one.

1.4. OBJECTIVES

Our research investigates the effectiveness of isolation systems that protect buildings from earthquakes. These protection systems consist specially of designed building foundations. Experts use computer simulations of such isolation systems to help them to make decisions about the needs of their designs and the supporting systems. To explore the effectiveness of adapting base isolation technology to assure seismic protection, a 40-storey building was isolated and it was simulated using ANSYS software with the input data of a model of a 40-storey building. Using the software, we evaluated the performance of the structure through multiple inputs and earthquake excitation values.

1.5. MOTIVATION

1. The current study deals with the possibility of earthquake damage in multi-storey building structures.
2. Small residential units or family houses are not discussed in this study.
3. Building design is important for the prevention or reduction of structural damage during an earthquake. The non-structural building elements are also significant, but we do not discuss them in the current study.

PART 2

LITERATURE REVIEW

It is not a new idea to isolate a building from the ground, which ultimately releases it from the effects of a devastating earthquake. Experts have made many efforts to isolate building structures since early years of the 20th Century. A German engineer J. Bechtold, 1907 suggested that a building base should be made up of granular substance. It is shown in Figure. 2.1. For designing an earthquake-resistant structure, many researchers have made remarkable contributions, which have partly resolved the problem. Glicksberg, 1973 and Mizuno, 2000 developed many isolators, which are found to be effective against devastating earthquakes.

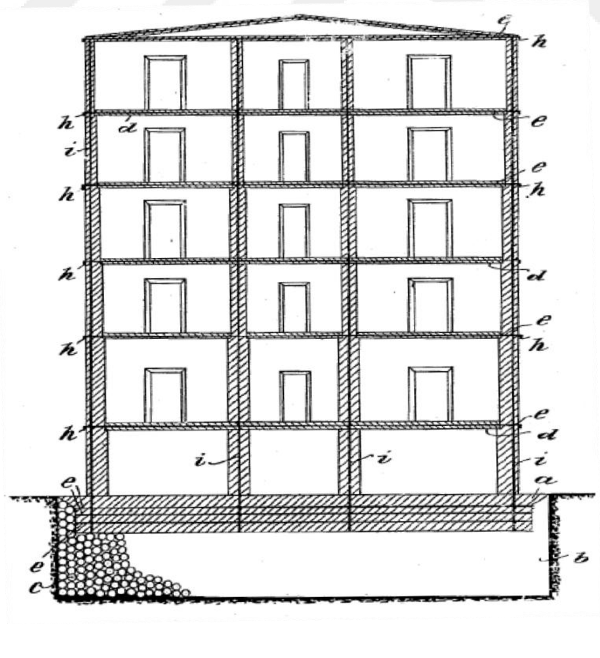


Figure 2.1. Earthquake proof building [3].

In 1998, 300 structures were erected, which utilized fluid inertial dampers technology. This technology was later utilized for military installations. This technology helps dispersing violent wind as well as seismic energies through its reliable design. Experts install inertial dampers in sizeable structures to dissipate destructive energies. These applications use fluidic inertial dampers. Their designs are inspired by the military designs originated during the Cold War era. They are advantageous because they have low project costs, less column stress and deflection, less quantity of construction material, and protection of architectural characteristics [4].

Researchers Braga, Gigliotti and Laterza [5] conducted some dynamic release tests, which produced a huge value of acceleration and displacement time histories. Analysis of acquired experimental data are now in progress, but first results confirm good behavior of Mixed system and its capability to solve some design problems due to high damage rubber bearing (HDRB) systems. The registered data are giving much suggestion for the design of Mixed Isolation systems, which are not taken into account by several codes as in the case of the Italian Guidelines for Seismic Isolation.

It is expected that equally reinforced buildings including the first traditional fixed-base structure B and base-isolated structure A. would be able to show some useful insights on the seismic behavior of different tyes of buildings. They are illustrated in Figure 2.2.

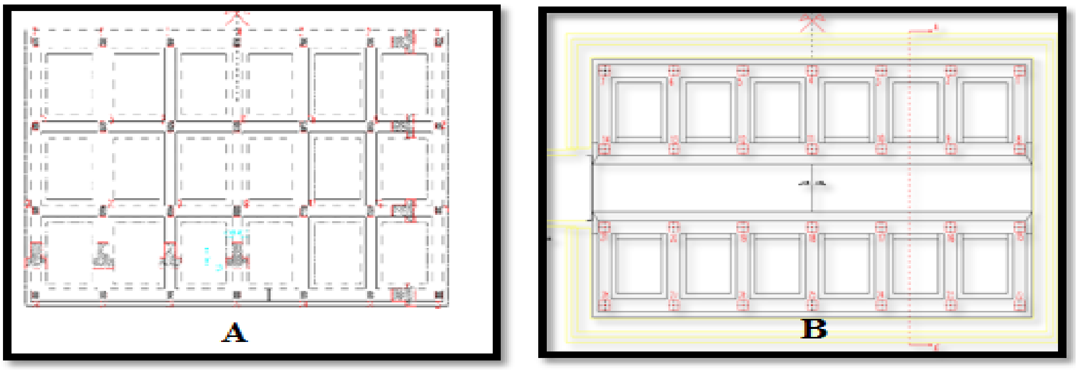


Figure 2.2. Fix base structural foundation for building A and B.

The rubber-bearings need repair whenever the building gets medium to large jolts despite the fact that using lead-rubber bearings for earthquake resistance is a useful technique. Some expert believe that the semi-activated earthquake resistance systems are better because they minimize the base-isolated buildings' response, which depends on their load [6].

It is a fact that the growth of latest earthquake protection methods using concrete and steel is improving, the growth of wood-based systems has almost stopped. It happened when light wooden structures disintegrated after excessive damage when the Northridge Earthquake took place in 1994. Another reason is that some impediments did not allow effective and necessary base-isolation to take place even in the presence of damping in wooden buildings [7].

It is a fact that high damping rubber (HDR) bearings have a complicated and difficult to understand its behavior, which is why, experts developed a phenomena-based model to explain the HDR two-directional shear force and the deformation response [8].

Researchers have investigated a latest but economical friction-viscous-elastic damper and its placement to isolate a structure’s foundation. They found that the version based on pure friction shows stability, easy manufacturing process, and installation time saving. It does not require for the installation process. A damper’s structural computational modeling and analyses have shown that even the seemingly best damping system is not without limitations [9].

Nowadays, some builders use storey-isolation or top-isolation for retrofitting an existing building while in some cases, they employ rubber bearings and slide friction layers. Many shaking table tests were conducted to understand new isolation systems. Researches on such possibilities have been conducted at Guangzhou University in China. The Chinese government has made efforts to maintain quality of rubber bearings, prices, and assured their large-scale use. Many studies and tests continue in Guangzhou University on effective isolator designs, possibilities for permanent isolation, and constant load tests of rubber bearings [10].

It is necessary to improve irregular horizontal and vertical irregular buildings through architectural skills, which can save life from major catastrophes. During a seismic movement, damage is done through many ways including structural damage, breaking of fixtures, turning over of furniture, and breaking equipments etc. A good earthquake-resistant option stops all kinds of damage; however, the design might contain some flaws or issues, which might not let the system bear pressures including wind-pressure and force of earthquake loads. Sometimes structural aspects are faulty and sometimes, the construction technique is inappropriate, having issues such as the turning-over problem and application difficulties [11]. In addition, many problems remain to be resolved, such as the use of control content to ensure safety in the event of malfunction or failure. Nevertheless, two desirable performance properties for base- isolated building in the future are:

1. Control of the displacement of the seismic isolation storey during a seismic motion that is bigger as compared to what was anticipated.
2. Ideal response control with respect to various outside disturbances such as not only earthquake but also wind and environmental vibration [12].

In a study conducted by [13] a base isolation system was discussed that incorporates a spring-cam system with a spherical support, which was specifically designed to protect a few-storey buildings from seismic movements. The dynamic behaviour of a three-storey concrete structure was investigated in the light of facts regarding Taft and El Centro earthquakes. Results show that maximum acceleration, displacement and shear force substantially reduced when the base isolation system was applied. The decreases were 93%, 24% and 87%, respectively in case of El Centro earthquake while they were 93%, 43% and 94% respectively for the Taft earthquake as indicated in Figure 2.3. The base movement is relative with respect to the ground having 0.15 m optimized length. At this point, compression of springs was not full. The highest value of vertical force was lower than 1.5% of the structural mass; therefore, its structural impact was negligible as compared to shear forces. It is a fact that this system relies on quick cam unlock process during an earthquake, the cam release controls should be dependable because the base-isolation is subject to El Centro seismic load.

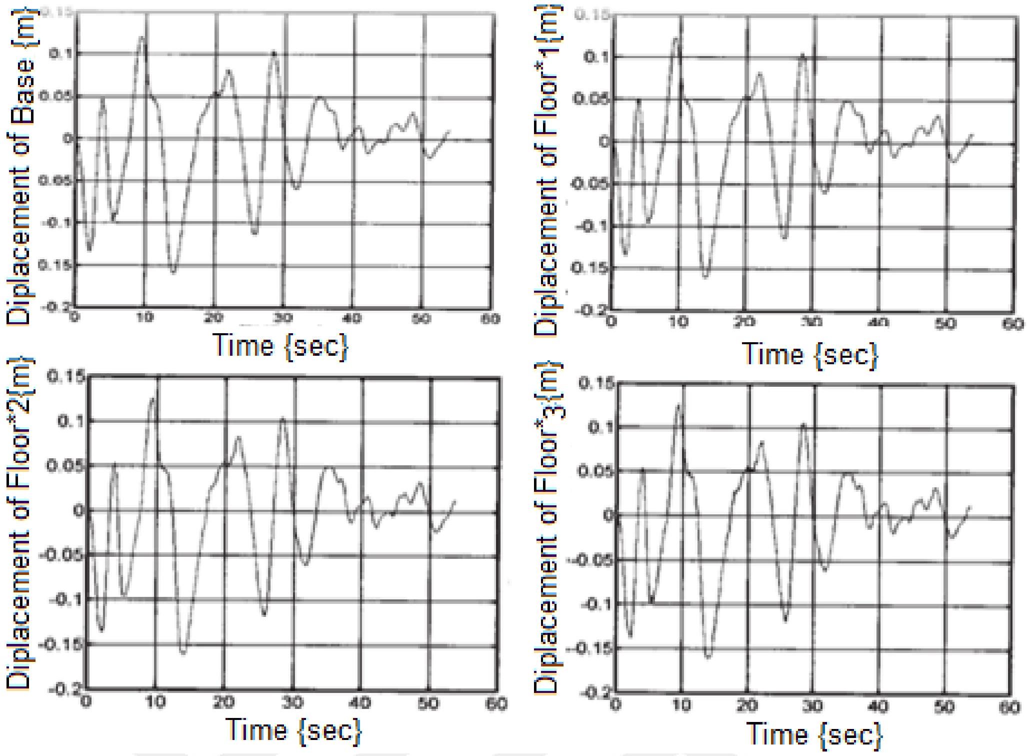


Figure 2.3. Displacement versus time responses in a base-isolated building.

Here, three isolation systems were separately and collectively tested. From this research, the researchers demonstrated that base isolation is an advantageous technique to diminish significant damages in structural elements and contents by avoiding the total transmission of the ground motion into the superstructure. Isolating the structure at its base lengthens the first period, hence provides high flexibility to this latter and shifts the structure from the dominance and severe region of ground motion, the lengthening of period was about three times. The friction pendulum system (FPS) provides less flexibility while comparing with the use of the other 1st category isolating systems. The use of friction pendulum system makes the structure moves horizontally with a magnitude much greater than in the case when using the LRBs having hi-damping rubber bearing system (HDRB) this feature of friction pendulum system can be demonstrated by the contact surface between the isolators and the superstructure.

Moussa Leblouba, 2007 investigated the fact that the time is structural mass-independent factor, which is another FPS property, and it can have benefits in terms of managing the building response. A required time period is chosen by selecting the curvature radius of a concave shape. It will not be different even when structural mass varies or becomes different as compared to what was taken earlier.

By combining a mega-structure with excellent stiffness and load resistance with a base isolation structure, the authors have achieved product design type architecture having a façade with high permeability in a white rectangular frame. This slender elegant form has a clear and outstanding presence within the context of the surrounding urban landscape. The merits of isolated structures in Japan are not only the improvement in seismic performance, but it also provides potentially large benefits for design and use in urban landscape [1].

Conventional earthquake-resistance depends on inelasticity of the physical system, which creates drifts and distributes a building damage, which is later difficult to handle and costly to repair. Self-centering rocking frame system offers and alternate to the traditional approach because it has fuses, which can be replaced and after an earthquake, it is not difficult to put them in their places. A steel frame controlled system is also shown in this research, and it removes residuals as it focuses on replacing the damaged fuses after the earthquake. Computational and experimental researches were conducted to find out and inspect the variables pertaining to the building design, which show the system’s viability. The results described herein are preliminary experimental and analytical investigation is forthcoming, [14].

There are two lead-rubber bearing designs called as LRB1 and LRB2 having a yield force Qy were taken, which were equal to 5% and 15% of a building mass. They were designed for protection against both medium and large-scale earthquake. The evidence shows that LRB1 was better for protection against an earthquake in the light of 1940 El Centro earthquake magnitude while LRB2 was found as helpful to deal with strong seismic jolts like Kobe earthquake 1995 [15].

These LRBs are easily available in the markets. Their installation needs just a testing machine with local isolator testing, so, it is feasible to manufacture them in countries like Iran. It is evident from past usage experiences that both construction experts and the people believe that base isolators have a capacity to assure long-term safety against seismic hazards, so, they are likely to be used on a massive scale in the future. Currently, their use in the structures is a giant leap forward [16].

When a hybrid isolation system (LRBs + FSBs) is used along with the technique called as rotational friction dampers (FDs) in the foundation, it enhances the structural performance by minimizing displacement, and with high shear; however, this system negatively affects the drift that increases flexibility of a structure [17].

Another research process was conducted to inspect a 3D, smart and base-isolated structure that was utilized as an ideal model to conduct numerical seismic control experiments [17]. It was pointed out [18] that the builders should be very careful while using SI in countries like Italy, where the law encourages designers to reduce the impact of an earthquake. Therefore, the process should be cautious whether it is installation or design, selection or maintenance throughout the lifetime of a building. If precautionary measures are not taken, and emphasis is maintained on traditional methods, the building safety will be less than the needed during a seismic movement. Experts have provided 3 options to design an earthquake-resistant structure. They allow minimum damage during a seismic movement. It is possible to combine their features, which allow higher loading and maximum base-isolation to protect important building structures. The damage-resistant designs are needed because it was observed during the Christchurch earthquake that the damages are beyond repairs. Now, builders are building new buildings in New Zealand according to principles, which allow very high damage-resistance than the already constructed ones [19].

It is necessary to install isolation systems in order to create more flexibility, damping and resistance to bear additional loads, and meet the needs such as economy, strength, installation ease and reliability. The overall structure should be supported by some discrete isolators, and their properties should allow uncoupling seismic movement. On the other hand, displacement/yielding depend on the effectiveness and quality of isolation installations because a superstructure acts as a rigid structure during a seismic activity [20].

The isolators prolong a natural vibration in sensitive equipments. In addition, they increase damping, which reduces bearing sizes, displacements, and contact area protection between a concave foundation and the articulated sliders, and it reduces damage whenever an earthquake hits [21].

Moreover, [22] conducted shake-table tests to describe isolation of structures that gave useful insights in the role of lead rubber bearing, cross linear bearing and triple pendulum isolation system in the context of seismic movement. They identified some information gaps, which exist in terms of installation of earthquake-resistant systems capacity to isolate structures. Some non-structural elements and some equipment were found vulnerable during a ground movement under high ground velocity and seismic movements with big vertical excitation components.

Seismic protection of buildings by seismic isolation is continuously improving since its early stages. New materials and shapes are contributing to the development of recent high performance devices. Architectural innovations are encouraged by the enhanced structural response achieved through seismic isolation. Developing countries may also benefit from this technology especially in the case of non-engineering structures [23].

Good top-storey isolation normally consists of a Magneto-rheological (MR) damper that has less dampering bearings, which decrease the intensity of an earthquake for a specific structure. Experts have developed a logic-based controlling algorithm to manage a typical smart top-storey isolation system having multiple-objective algorithms. An isolating drift and the response to the flow acceleration have been applied with the help of objective functions [23]. In mechanical seismic isolators, there are three types of control systems: passive, active and hybrid control systems [24].
New mathematical models of lead-damping rubber bearing (LDR) and lead rubber bearings have been presented by [25] when they analyzed base isolators both with and without focusing on the design under seismic movement. The viscous damping in a lead damping rubber bearing means that there is no substantial capacity to dissipate energy. Here, effective damping β_{eff}=3% while varying damping displacement D=T_r that is a rule for calculating effective yield strength in a lead damping rubber bearing.

A lead rubber bearing's yield strength can be calculated through finding the yield stress in a lead-core. This was performed and exhibited by [25]. Also, Gu et al. [26] described the design and features of the magneto-rheological elastomeric base isolator described and utilized by incorporating it within a 5-storey benchmark-building model. The classical linear optimal control method is applied in real-time to control the semi-active magneto-rheological elastomeric isolator to achieve vibration suppression under various earthquake excitations. Series of extensive simulation studies was conducted for comparing effectiveness of passive base-isolators and controlled base isolators having a linear and quadratic regulation method. The numerical results support passive base-isolators for reducing the acceleration. However, it is not able to reduce the inter-storey drifts of simultaneously every floor. Additionally, passive isolated model's performance depends on the type and intensities of the earthquakes [26]. Moon et al. [27] conducted their analyses with the help of LRBs and a base-isolator. There were some steel shims between layers of rubber and the laminated rubber bearing that utilizes its flexible nature for deflecting the energy of an earthquake and also uses their plastic deformation property to absorb the vibration energy. Moreover, the core is made up of lead that further dissipates the seismic force. In this case, steel components of laminated rubber bearings were made up of elasto-plastic substances while rubber is already hyper elastic, and lead is elastic as well.

A non-linear analysis of the earthquake emergency response proves that the additional isolated upper floor (AIUF) acts like a turned mass damper (TMD) while the earthquake load pressures a structure which can be decreased by average 2.5 times.

The concept of additional isolated upper floor is part of new roof isolation that takes the shape of isolated upper slabs (IUS) to protect against a devastating earthquake in a typical 12-storey commercial building. This structure, its bearing information, its soil, and its placement were discussed. It was suggested that the attic floor slab should be moved upwards and installed in a place where base isolation system is located. This turned the slab into a single mass tuned damper [28].

Preliminary studies that discuss base isolation throw light on advanced boiling water reactor (ABWR) that indicates that this system can effectively reduce the building's reaction to the earthquake. Also a reduction in construction cost is expected in the base isolated reactor and building controls. By adopting the base isolation system, advanced boiling water reactor could be built on a site where the construction of non-isolated type of plants is deemed difficult due to high seismic intensity. Therefore, its use gives more freedom in the selecting site. This research found that base-isolation applies to the advanced boiling water reactor plants. A study was conducted on earthquake safety of two reactors. One had base-isolators while the other one did not have it, which shows that the isolated structure enjoyed better safety during an earthquake as compared the structure without base-isolation given that the experiment was conducted in a place having hard rock's [29]. Trials show that dampers, which belong to the pure friction category, exhibited appropriate and useful behavior. The dampers' electronic modeling and structural analyses show that the dampers are actually effective. The trials also show the limitations of installing them. They can be easily produced and placed in the buildings. Since the raw material is easily and readily available, a damper is economical to manufacture and use. Moreover, replacing a damper is easy and again economical; however, under normal conditions, they do not need repairs or replacement [30].

Another paper has reviewed key changes to the design provisions for composite construction, highlighted recent research on composite structural systems, and presented an example of a self-centering articulated use system that offers enhanced performance under seismic loading. These examples demonstrate the trends of steady continual improvement to design provisions and development of new systems to satisfy the ever increasing demand for better performing structures as well as provide a glimpse of where the steel and composite construction may be heading in the future [31].

PART 3

THEORETICAL BACKGROUND

3.1. 1. INTRODUCTION

Earthquakes take place whenever the Earth's surface shakes and releases seismic force that quickly moves the giant crust along a fault. These faults are points where the crust is broken. Their length is a few hundred kilometers and depth varies from 10-20km in the crust.

In case of earthquake, there is a specific place on a fault surface, from where, a movement actually initiates. That place or point is called as focus. The seismic waves discharge energy from focus to outward direction. The foci of an earthquake exist within a certain depth range. The shallow earthquakes have the focal depth of about 70 km from the surface, intermediate earthquakes are 70 to 300 km deep and deep ones can be from 300 to 700 km.

The earthquakes have some subduction areas, where plates join the mantle. Shallow earthquakes are more damaging because violent seismic waves move through short distance to reach the surface. Our primary focus is the effect of an earthquake on a constructed structure. Most of the governments have specified building guidelines, rules, and codes especially in those areas, which are highly vulnerable to earthquakes.

Before analyzing the details, we should comprehend exactly how earthquakes affect structures. We also need to understand as to how a structure can resist the power of earthquake. An earthquake is a highly noticeable phenomenon that takes place on the Earth's surface. Seismic earthquake takes place because of deficiencies within the Earth's body, which become so devastating.

People experience earthquakes, when an extreme force shakes the surface. When an earthquake hits the surface, sometimes, it makes cracks on the surface. Another hand, when the effect of the earthquake does not fully reach the surface, cracks do not appear [32].

3.1.2. History of Earthquakes

Tachu Naito is one of the most important researchers and experts on earthquake since 1920s, who is known for his rule called as slide rule (14 cm, 5.5 in), which he learnt from his teacher Riki Sano. Naito used this rule for many years in order to create resistance against forces and uncertainties. Japan has been subject to earthquake-related devastation for centuries, so naturally, it focused on earthquake and disaster mitigation. The University of Tokyo has been conducting researches on earthquakes since 1870s. Besides that the University of Edinburgh and the University of Glasgow have conducted significant researches on the topic.

S.L. Kumar, who is an Indian earthquake expert and father of modern earthquake engineering, presented the idea of earthquake-resistant metal reinforced masonry, which was effective during the Quetta Earthquake 1935, and that resulted in the enforcement of seismic building regulations. He also developed the earthquake-resistant concept of railroad in the days of British India. His use of reinforced concrete that gained wider popularity but he himself wrote that it is not possible to construct buildings in large numbers with it because it is costly.

He built many earthquake-resistant buildings using iron and steel. Old iron railway lines were cheap and the gigantic railroad system could easily supply them. Structural engineers recognized Kumar's efforts and learnt a lot from his experiments but today's sophisticated technologies have given better options, which allow engineers to design earthquake resistant buildings spending within the budgetary limits [33].

Construction planners usually select building materials based on their financial interests, so they mostly choose materials irrespective of their properties, and besides, they create value by improving the architectural qualities. China has a whole history of devastating earthquakes but even now, its earthquake resistance is inadequate.

3.1.3. Period of Vibration

Earthquakes are a consequence of stun waves, which move in all directions until they reach the Earth's surface applying both horizontal as well as vertical forces on the surface. A vast majority of building designs support vertical load because construction itself is a major form of load, so they can resist vertical forces or up-down seismic motion. One the other hand, constrain waves force structures backwards and forwards when an earthquake hits it. If the building is constructed right according to the building codes, it will provide better resistance and the damage will be minimized.

When the Earth's surface vibrates forwards and backwards, each cycle of vibration is termed as time of vibration, which is a very significant factor for determining as to how a building would response in case of an earthquake. The buildings, which have wooden frames, their vibration period are just half second, which implies that those structures have full seismic motion at the rate two times per second. During a strong earthquake, the seismic movement continues for almost 15 seconds, which means that the mentioned building structure will be shaken almost 30 times.

Vibration periods have different aspects and measurements of different dimensions. For reliable earthquake resistance, every segment of a building should be interlinked and strongly linked with the whole. Some building inconsistencies emerge due to excessive stories, porches, and chimneys. Retrofitting is a useful measure to protect buildings from seismic waves. It secures people living in the buildings. Retrofitting protects against the future damages, and besides, insurance companies feel no hesitation to insure retrofit buildings against the possible damages. Still, economic priorities and building investor's financial conditions determine whether a builder would go for seismic retrofitting or not.

California has enforced extraordinary building laws in 1960. Its state government has laid down following guiding principles for constructing buildings:

1. Compulsory use of stay bolts to secure a ledge plate.
2. Use of dividers on edges for people with disabilities, which are not made of a corner metal, plywood or wood props.
3. Construction of 1st storey dividers, which should not be constructed using plywood/inclining metal/wood supports.
4. Assure to establish edges using reinforced technique.
5. Construct dividers using unreinforced technique.
6. Construct living rooms on top of garages.
7. Install a fully functional water heater [34].

3.1.4. General Isolators

The traditional concept of seismic isolation is indeed an expensive method to reduce the earthquake's impact; so, it is possible to implement it in highly important buildings. In case of few storey buildings, providing lateral resistance is easy. Base isolation protects building constituents.

Some base-isolation systems are equipped with roller bearings and friction dampers, which perform with considerably low friction value $\mu < 1\%$. They are added to either lateral viscous dampers or rubber bearings for assuring the needed stiffness and resisting wind pressures as well as seismic deflections. Normally, researches do not include base-isolation requirements. In addition, there is a need for a restoring force to maintain a building's centre after a seismic jolt, which is possible by installation of rubber bearings or rollers.

Governments spend huge sums of money to fund researches for studying, understanding and developing some active control techniques to deal with seismic shocks. Japan has gained reasonable success in this context where large numbers of buildings are equipped with active controls. Many experts have recommended developing smart and active isolation systems but many concerns have been raised against that approach because their effectiveness is difficult-to-prove; therefore, they can not be considered as appropriate for low rise buildings.

Base-isolation systems are available in two popular forms. One of them is elastomeric rubber-steel plate bearing system, which have bearings placed vertically for stiffness and horizontal ones, which are flexible for horizontally isolating a structure in case of an earthquake. In this context, energy absorption is essential, which is possible by lead core or damping rubber. Another form of base-isolation system has rollers, friction pendulums or sliding bearings. To assure sliding movement, materials having less friction like reinforced Teflon are used to make sliding areas. The sliding bases creates isolation through reducing effect and limiting the force transfers by isolating the interface, which absorbs the energy of an earthquake [35].

3.1.5. The Concept of Base Isolation

Base isolation is a very significant and practical concept that interposes parts of a building having less horizontal stiffness between the foundation and the building structure for decoupling it and releasing it from the possibility of seismic horizontal motion. The first dynamic mode deforms in case of base isolation when a rigid structure is erected above. This deformation takes place within the building that has orthogonal shape facing the ground motion in the first mode. The high modes play no role in any kind of motion, so, the ground energy does not transmit towards the building. Obviously, the base isolation framework does not absorb energy from an earthquake excitation but it detects it through the system dynamics, which does not depend on a damping level. Dampers are important to suppress resonance at the isolation frequency.

3.1.6 . Effectiveness of Base Isolation

A main base-isolation function is reducing base shear. For this purpose, the period ratio T_b/T_f should be as large as practical, otherwise it will be harmful. For instance, during 1985 in Mexico City, the earthquake excitation that occurred in a one-storey building with pseudo-acceleration value :

A (T_f ,ξ_f) = 0.25□ associated with $T_f = 0.4sec$ and ξ_b=10 for the isolated structure.

The ratio $A(T_b, \xi_b)$ / $(T_b, \xi_f) = 0.63/0.25 = 2.52.$
It means that the base shear in the base-isolated building is 2.5 times the base shear in the fixed-base building as $Tb >> f$ [36] .

3.1.7. Classification of Earthquake

Owing to the difference in movement between the plates that are in motion, three types of plate boundaries are found to exist along their edges.

3.1.7.1. Spreading Ridges

Spreading edges or dissimilar limits are regions along the edges of plates, which move separately. This is the area where the less thick liquid shake from the mantle rises upwards and turns out to be a piece of outside in the crust of cooling. Most astounding rate of spreading or development Pacific Ocean edges and the least rate of spreading happens along mid-Atlanticedges. By and large, spreading edges are situated underneath the seas. A couple of zones where the spreading happens along them in East African fracture valley and Iceland.

3.1.7.2. Convergent Boundaries

The convergent boundaries are formed where the two plates move toward each other. In this process, one plate could slip below the other one or both could collide with each other.

Seduction Boundaries

These boundaries emerge when lithosphere in the ocean merges underneath lithosphere of another ocean. It also merges when an ocean's lithosphere gets underneath continental lithosphere forming an oceanic trench. Whenever an ocean's lithosphere plates strike each other, a subducting plate moves deep down, which results in some melting. When oceanic lithosphere plates strike against a continental lithosphere plate, the oceanic plate submerges because of its high density as compared to the afore-mentioned plate. In the depth, this plate melts when it comes in contact with magma, and some of its part gets in a fully molten shape. The magma-turned-plate moves up for erupting volcanoes and forming islands. This type of islands is called as island bends. One of the areas around Indian peninsula where seduction process is in progress is located near Andaman-Sumatra region, where the Indo-Australian plate is subducting below the Andaman and Sundaplates.

Collision Boundaries

Whenever a couple of continental lithosphere plates strike each other, their sub-duction process stops and they form mountain ranges because they squeeze each other raising the continental crust.

3.1.7.3. Transformation Boundaries

Transforming boundaries occur along the plate margins where two plates moves past each other without destroying or creating new crust.

Performance-Based Design

If we look at the international trends regarding earthquake-resistant design strategies, we must remember that great structural losses took place in Christchurch as a consequence of earthquakes. That resulted in a debate for disaster risk reduction in future.

3.1.8. Design Capacity

The international building codes have underlying seismic design philosophy. Its guiding principles are as follows:

1. Minor/small scale earthquakes shouldn’t create any kind of damage.
2. Moderate earthquakes may result in some repairable damages.
3. Large-scale earthquake might result in extensive damages but they should not result in building collapses or life loss.

The financial benefits of earthquake-resistant buildings are universally acknowledged. A building should withstand an above-average earthquake [37]. The ongoing design strategies are more about ductile designs, which have the capacity to bear many extreme loading cycles. They require inelastic and stressed materials, which do not lose their strength during earthquake. Experts including Prof. Tom Paulay and Bob Park developed a separate design ideology at the University of Canterbury during the late 1960s and early 1970. The fundamental point of this approach is that the designer places the weakest point of the construction according to his/her choice. That weak part/link acts as a "ductile fuse," which saves the building from a total collapse. In this case, the building sways but does not collapse whenever an earthquake hits it [37].

3.1.9. Ductility

During the Christchurch earthquakes, experts observed many issues, which took place primarily because of high ductility (inelasticity), which was detrimental to building structures during violent earthquakes. A ductile structure does not immediately fail, so, the chances of catastrophes are very thin. The plastic pivots result in excessive displacement when an earthquake hits. In this case, the building vitality retains when the harm is controlled through some selected segments of a building. For considerable ductility, a structure should have high displacement and it should not lose strength. Nowadays, building designers focus on ductility of a design. They have to take care of a lot of things including building codes, regulations, and priorities of investors/owners, who focus on minimizing cost of construction. Along with other promising features, ductility is indeed a valuable feature because:

1. Ductility of building components absorbs earthquake’s seismic energy.
2. Ductility makes building resist small seismic pressures through their elasticity, which is possible by using economical building materials.
3. Unlike brittle/fragile structures, ductile structures do not suddenly collapse whenever a seismic force exerts more force than their strength/displacement limit.
4. Ductility of a structure offers better human safety whenever any intense earthquake hits the structure. During the Christchurch earthquakes, it was observed that ductile buildings deformed when a very high intensity earthquake had hit it. Still, ductility is one of the most needed attributes, which are needed in the post-modern building designs. The ductility is effective only if it is created in combination with latest design methodologies because they decrease residual damages as well as deformations. Designers should design ductile buildings with great care because structural ductility should be according to the given limits. Experts like Paulay and Priestley,1999 believe that strength and displacement should be in proper combination and the ductility level should be appropriate for both of them. It is obvious that the strength decreases when a designer increases planned ductility and a shift takes place from elastic to a ductile response. In this case, the building’s displacement will remain the same irrespective of ductility [19].

3.1.10. Classification of Isolation Systems

3.1.10.1. Approaches to Base Isolation System

For effective accomplishment of base-isolation, passive installations such as dampers or isolators are installed in a structure. This isolation provides flexibility as well as damping, which are essential for successful base-isolation and the required stiffness for service loads. Other useful alternatives to this approach include elastomeric, sliding and hybrid systems. We will discuss them as well. For basic controls, structural systems are oriented with inactive controls. For this purpose, isolators also play a very important role because they end segregation. In addition, dampers are useful for dispersing energy in a system. The regular isolators and dampers are arranged and shown in Figure 3.1 and Figure 3.2 below which is showing the arrangement of dampers and isolators.

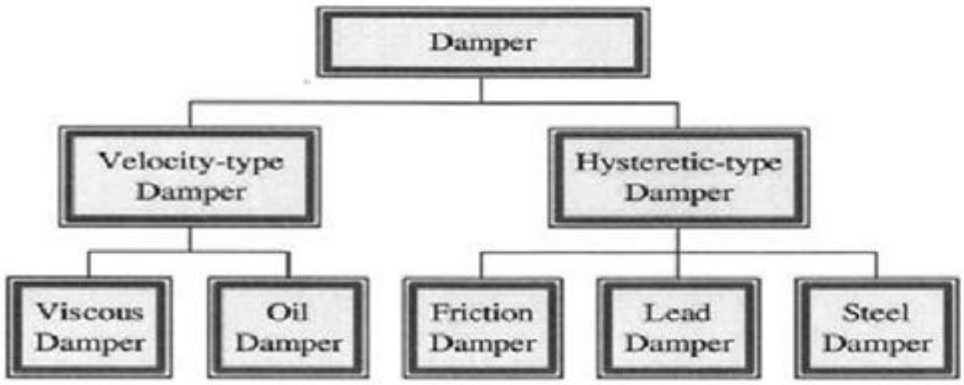


Figure 3.1.The classification of dampers [6].

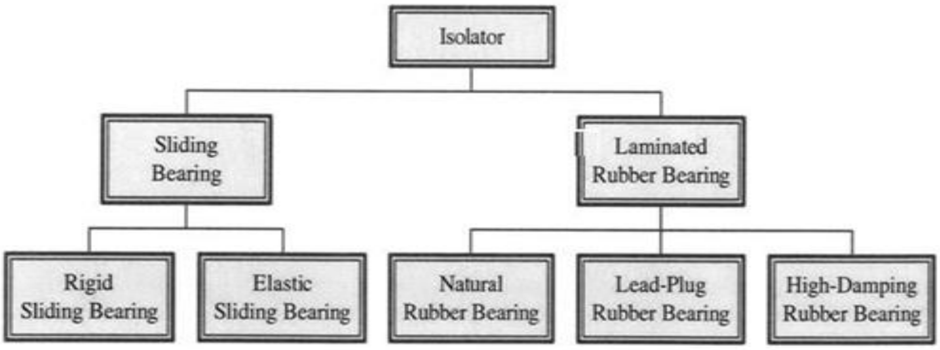


Figure 3.2. The classification of isolators [6] .

3.1.10.2. Elastomeric Bearings

They help creating base-isolation, and they are popular during the last few years. The elastomeric bearings are either made up of neoprene or common rubber. According to this method, a designer or engineer decouples a structure using the horizontal component for protection during an earthquake. It is possible to control the impact of ground motion through interposing low and horizontally stiff layer, which exists between the foundation and the structure Figure 3.2.

They are also called as seismic base isolators, and they are quite popular among experts because they provide satisfactory earthquake protection, which is possible using some structural parts, and help decoupling a structure from its sub-structures.

Base Isolation Systems

Base isolators are considered as highly effective for protection during an earthquake because they work with the help of passive controls. They consolidate a structure and improve its survival during an earthquake with the help of a proper plan and a subsequent modification.

Moreover, it is proven that base isolation increases a building's performance and seismic survival. In fact, base isolation does not create earthquake resistance. It is equipped with systems helpful for isolation. The following two factors are important in this context:

1. Isolating units are basically the building units for base-isolation, which help decoupling a structure.
2. The elements, which isolate a base of a structure, have no decoupling effect.
3. Isolating elements consists of shear/sliding properties, which are needed for base-isolation during an earthquake. It was observed in Pasargadae, which was a city of ancient Persia, and it dates back to 6^{th} Century BC. The city was constructed with the help of stone as well as mortar. On the top, some smooth stones were attached together, which seemed like a plate that survives even if an earthquake hits with its continuous backward and forward movements.

This technique is useful for latest designs and protection during an earthquake. Many top US landmarks, for example, San Francisco City Hall, Pasadena City Hall, County Building, and Salt Lake City have base isolation systems. It works through unbendable elements and systems in a building, which create a P-Delta Effect. [38].

On small-scale, base isolation is possible even to protect one room. The isolated floor protects equipments from an earthquake. This was used for protecting statues, antiques, and artworks in different museums and art galleries [39].

Base isolation is utilizable for mitigating disaster during an earthquake, and it is now part of most of the construction projects. Because there is non-linearity, the structural design of base-isolation normally utilizes non-linear time analysis. This process needs finite base-isolation models. Moreover, during the beginning phases of the design, some structural definitions are not properly defined, so, for simplicity, approximate analysis for base isolation is used. A best-known approximation process offers its equivalent linear analysis [40].

A major base-isolation element is flexibility, which is created between the foundation and the structure. When it happens, the isolators continuously absorb energy, which increases system damping, and that further minimizes a seismic movement. The base-isolation seems like a series of cushions made up of rubber cushions. The base-isolation does not work well with all structural forms. The high-elevation buildings or those having soft soil underneath are inappropriate to be earthquake-protected through base isolation. It is useful only for low and medium elevation buildings located on hard soil.

Laminated Rubber Bearing (LRB)

These rubber bearings are part of popular elastomeric isolation systems. The seismic structural response analysis of multi degree of freedom buildings for the rigidly supported and isolated cases is investigated. that the proposed system is implementable and can result in orders of magnitude reduction in the transmitted force to the structures., which minimizes a structure's bounce at the time of earthquake. Installation of steel shims is useful because it stops rubber from coming out; therefore, the process involves linear force deformation behavior with increased damping, which is illustrated in Figure 3.3.

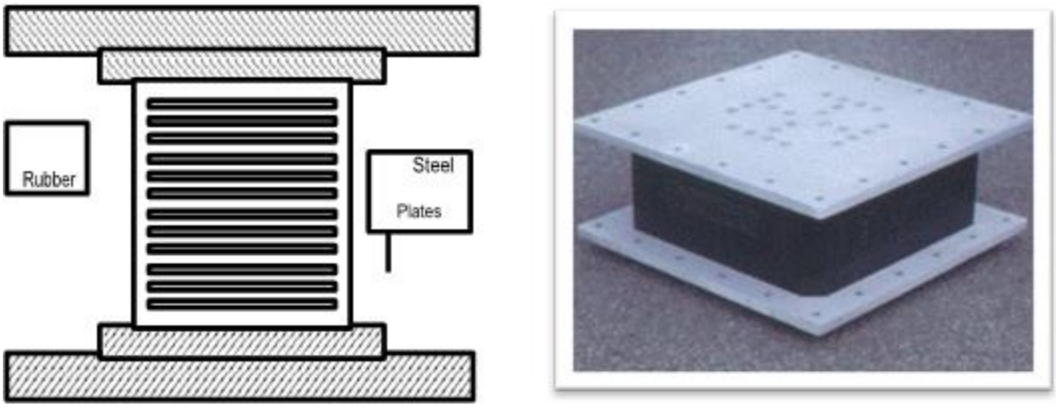


Figure 3.3.The rubber Steel base isolated system [41].

The restoring force is expressed by equation:

$$F_b = c_b \dot{x_b} + k_b x_b \quad (3.1)$$

Here c_b and k_b represent damping and bearing stiffness.

The mentioned damping and stiffness in a LRB system have specified values of isolation period (T_b) and the damping ratio (ξ_b). F_b the restoring force, x_b the relative base displacement , $\dot{x_b}$ the relative base velocity.

Their mathematical relation can be given as follows:

$$T_b = \frac{2\pi}{\omega_b} \text{ and } \qquad \omega_{b=}\sqrt{\frac{k_b}{m}} \tag{3.2}$$

$$2\xi\omega_b = \frac{c_b}{m} \tag{3.3}$$

$$M = m_b + \sum_{j=0}^{n} m_j \tag{3.4}$$

Here, M represents mass of the base-isolated building, ω_b the isolation frequency of the bearing, m_j represents superstructure floor while m_b represents base mass.

Lead-Rubber Bearing

They are quite like the previously mentioned laminated rubber bearings. The only difference is that they have a central lead core, which provides extra rigidity and more energy dissipation, which is very helpful against minor winds and earthquakes as show in Figure 3.4.

The lead core has more energy absorption properties, and it lowers the isolator's lateral displacement. They provide extra damping with the help of hysterical high-yielding core made up of lead. The hysteretic bearing loop shows bi-linear deformation. The expression to find out the restoring force is given below.

$$F_b = c_b\dot{x_b} + \alpha k_b x_b + (1-\alpha)F_y Z \tag{3.5}$$

In this equation, F_y represents a bearing's yield strength, α shows post-yielding to pre-yielding stiffness ratio, k_b means a bearing's initial stiffness, c_b represents a bearing's damping, and Z represents non-dimensional hysteretic displacement. A lead rubber bearing has certain specific values of parameters. They include isolation period or T_b, damping ratio ξ_b and normalized yield strength F_0. We can obtain T_b and ξ_b through some given equations:

Equations 3.2 and 3.3 are constructed on a bearing's post-yield stiffness.

Here, F_0 can be given as:

$$F_0 = \frac{F_y}{M_g} \tag{3.6}$$

Here, M_g is acceleration due to gravity [42].

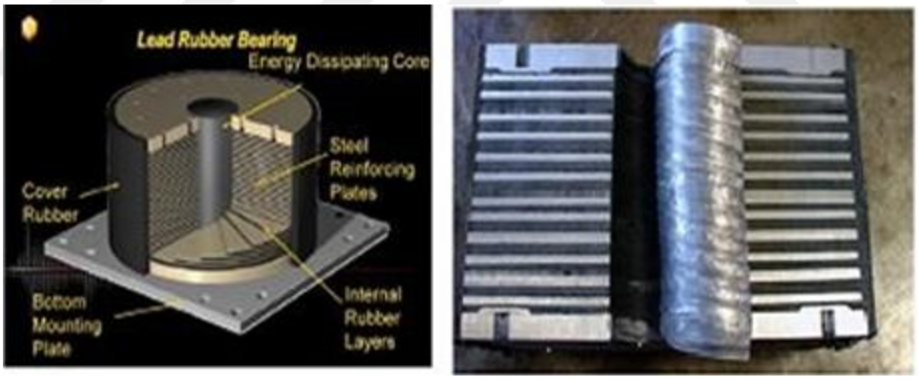


Figure 3.4. The lead rubber bearings isolated system [43].

3.1.10.3. Isolation System Based on Sliding

If we measure the base isolation that uses a sliding system, it will be an easy approach. A sliding system reduces acceleration of the floor but loses the shear displacement between the structure and the foundation. It is possible through adding friction using geometric accessories. Experts believe that small buildings constructed on traditional masonry principles, are not possible to be base-isolated in an economical way with the help of elastomeric isolators. So, a sliding system is an economically viable solution to the earthquakes. Moreover, a sliding system has the capacity to bring a structure back to its position, when the earthquake becomes over. This is an effective property because it leaves a building in an intact form. This phenomenon has been illustrated in Figure 3.5.

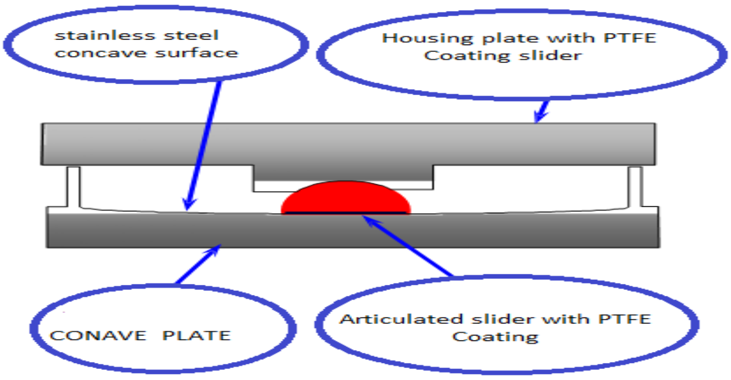


Figure 3.5. Schematic diagram of sliding system [44].

Flat Slider Bearings

Sliding takes place along a horizontal plane.They don't have a restoring reserve and are used in parallel with other devices, typically elastomeric bearings.

In Figure.3.6a, A section through a pot bearing is presented. The pot contains a portion of elastomeric material that permits rotations. Another similar sliding bearing is the rail roller bearing. The sliding occurs on two orthogonal rails in horizontal direction Figure.3.4b.

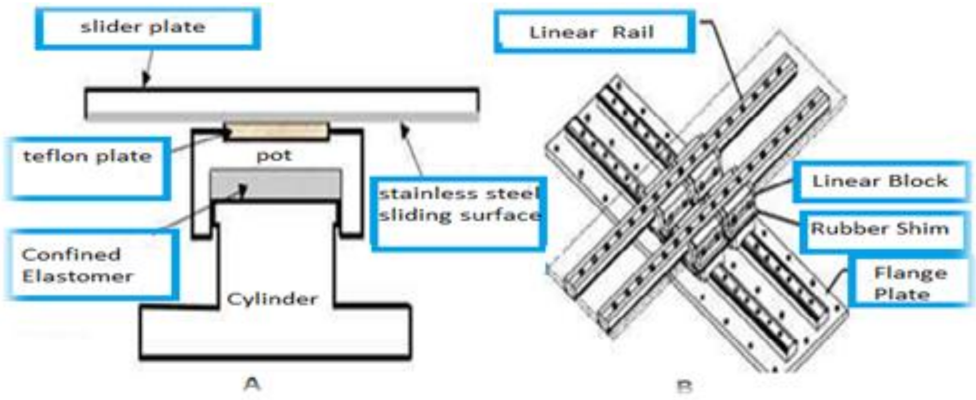


Figure 3.6. Horizontal sliding bearings: a) Pot bearing, b) Rail roller bearing [44].

In Figure 3.7. It is presented the layout of base isolation using rail roller bearings implemented by the Japanese company THK. The rail sliding device has a very low friction force and it is attended by laminated rubber isolators for reinstating and viscous damping devices. Due to its tensile strength, it can be unitized to isolate tall buildings.

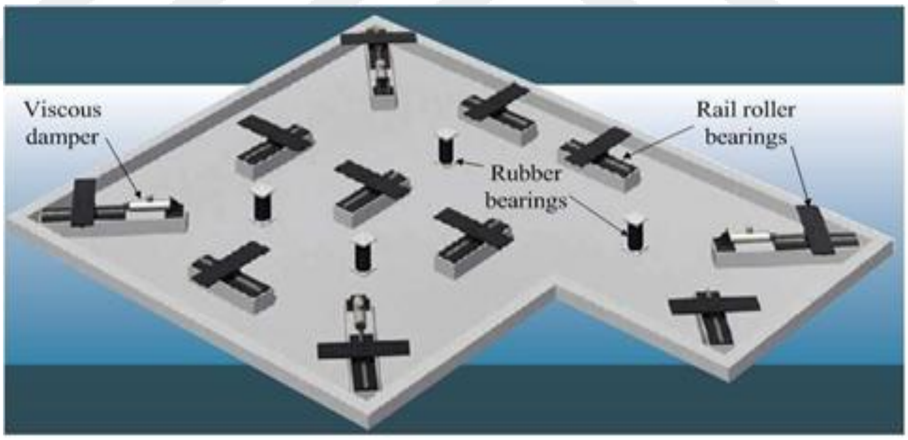


Figure 3.7. THK base isolations system [42].

New materials are tested to find inexpensive devices intended for non-engineering use in developing nations. Acceptable results were obtained for wood-stone and granite-marble contact surfaces.

Friction Pendulum System

It is a very effective method to create base isolation as it uses sliding accessories. A sliding process shows good performance and assures safety during a violent earthquake. It is considered as useful to reduce the high superstructure acceleration. They are insensitive to the earthquake frequency because their sliding process reduces/disperses the seismic energy into several and low intensity frequencies. A sliding base-isolator is considered as better than traditional rubber bearings because they develop friction in the foundation, which is proportional to that building's mass. Moreover, the centers of mass and sliding support resistance correspond to each other; therefore, it diminishes the torsion impact created by an asymmetric structure.

Experts have amalgamated sliding bearings technique with pendulum type response, which results in a useful and inspiring isolation system called as friction pendulum system FPS [45]. It is illustrated in Figure 3.8a. In Figure 3.8b we have illustrated a simple pendulum response model that has some similarities with the frictional pendulum system. The sliding technique consists of a slider above a chrome surface in concave spherical shape. When a slider faces a bearing material, it touches the smooth chrome surface that creates friction, and the concave foundation creates a restoring force. This system works just when the force of earthquake exceeds the static friction value. FPS is a horizontal force, which equals the sum of mobilized friction and restoring force, and it emerges when a building rises on a spherical concave foundation [46]. These forces, their actions, force-deformation, and the FPS system are illustrated in Figures 3.8c and Figure 3.8d.

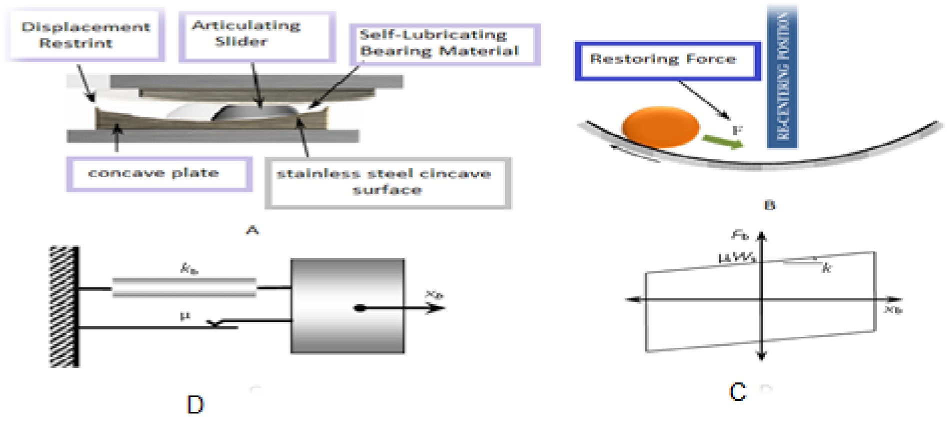


Figure 3.8. Friction pendulum system: a) FPS, b) Pendulum action, c) Schematic diagram of FPS; (D) Force-deformation behavior of FPS [43] .

The system provides a resisting force, which can be mathematically calculated as follows:

$$F_b = K_b X_b + F_X \tag{3.7}$$

K_b represents bearing stiffness, which is supplied through the inner gravity of the concave foundation while F_X represents force of friction.

This system is based on two types of variables:

1. Isolation period of a bearing, denoted as T_b, which is curvature radius-dependent,
2. Coefficient of friction μ. Isolation stiffness k_b should be according to the isolation period value, which can be calculated through Equation 3.7.

The Trench and Trajectory Friction Pendulum Systems have diverse properties on the two orthogonal headings Figure 3.9a. It is suggested for structures having possessed different regular frequencies in two headings. The Triple Pendulum bearing is a multi-stage bearing that progressively shows diverse hysteretic properties at various phases of uprooting reaction. It consolidates four sunken surfaces and three free pendulum components Figure 3.9b. The firmness and damping of the three mechanisms are chosen in light of numerous levels of seismic request.

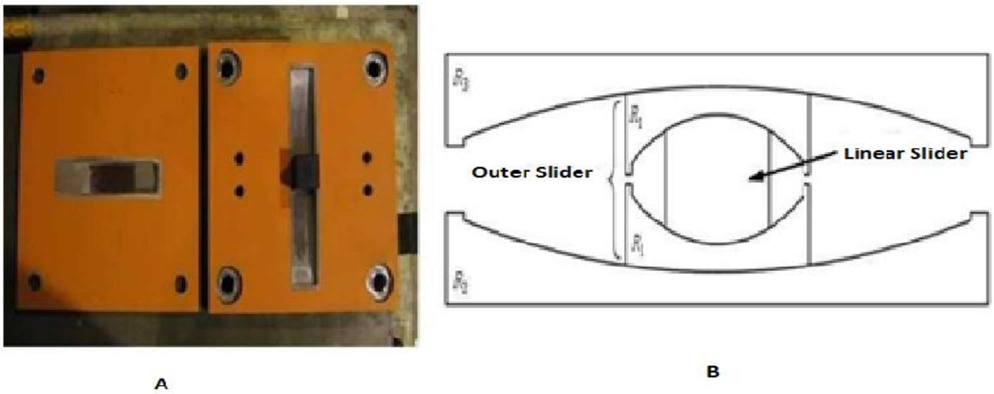


Figure 3.9. Optimized friction pendulum systems. a) Trench and trajectory friction pendulum system TFPS, b)Triple pendulum TP bearing [44].

3.1.10.4. Damper Description and Principle of Action

We will first describe different parts of a damper. It consists of a vertical plate, two horizontal plates, and two friction-pad discs. They are illustrated in Figure 3.10.

The length of vertical plate is H that is linked with the girder with the help of a hinge, which augments relative rotation that takes place among side and central plates. It improves the system's energy dissipation. Edges of side plates are linked with the inverted V-brace maintaining distance *r* from center of FDD. The pretension bars are used for avoiding the compression stress and resulting buckling. The brace bars are linked with the help of pins on both edges with a damper.

The two side plates and a central one enhance the surface area for friction, which improves symmetry that is required to obtain a device's plane action. The pre-tightened bolt interconnects all the three damper plates. The adjustable bolt also controls the interface compression that is exerted on plates and discs. For maintaining continuous clamping, many spring washers are needed. The hard washers are used for placing between springs for preventing steel surface marks, which might be created because of spring washers and compression. The high-quality steel grade S235 is used to manufacture the device plates. For meeting the quality needs of the industry, local steel fabricators prepare steel plates and specimens without any effort to manage or change the steel flatness and the damper's dimensions [47].

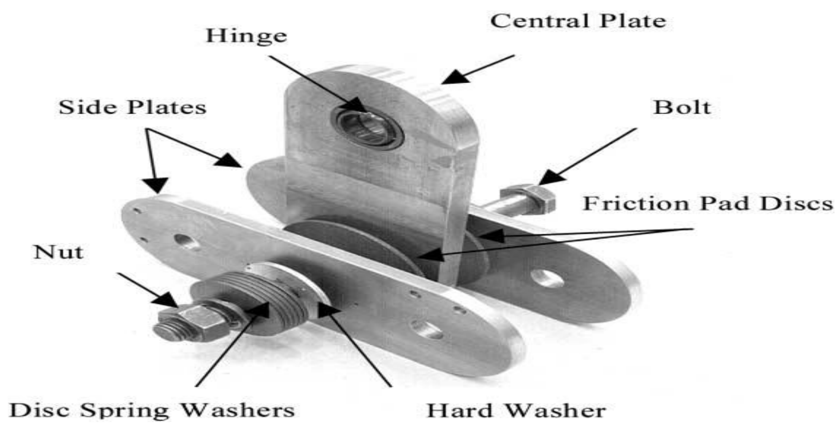


Figure 3.10. Components of FDD [47].

Devices for Supplemental Damping

Many additional and supplementing devices are available for improving a building's damping, which have the capacity to absorb the seismic forces or improve the structural damping that enhances a building's overall response to an earthquake. They work in combination with the existing base-isolators or used on the structural top. They are used to minimize damage or when the existing earthquake resistance is insufficient against the recorded historic seismic movement.

These devices are designed for those structures, which do not have the needed base-isolation. They have the needed elasticity for a few-storey buildings and they help controlling displacement, which is possible through installation of damping devices as they are good absorbers of most of the earthquake energy. A good option is retrofitting that is somehow easier to install as compared to installing base-isolation systems. Moreover, it facilitates the occupants of a building.

When new devices are installed in a structure offering more damping, the earthquake energy minimizes because damping minimizes the foundation's response. Experts use different damper types for mitigating earthquake disaster. They are shown in Figure 3.11.

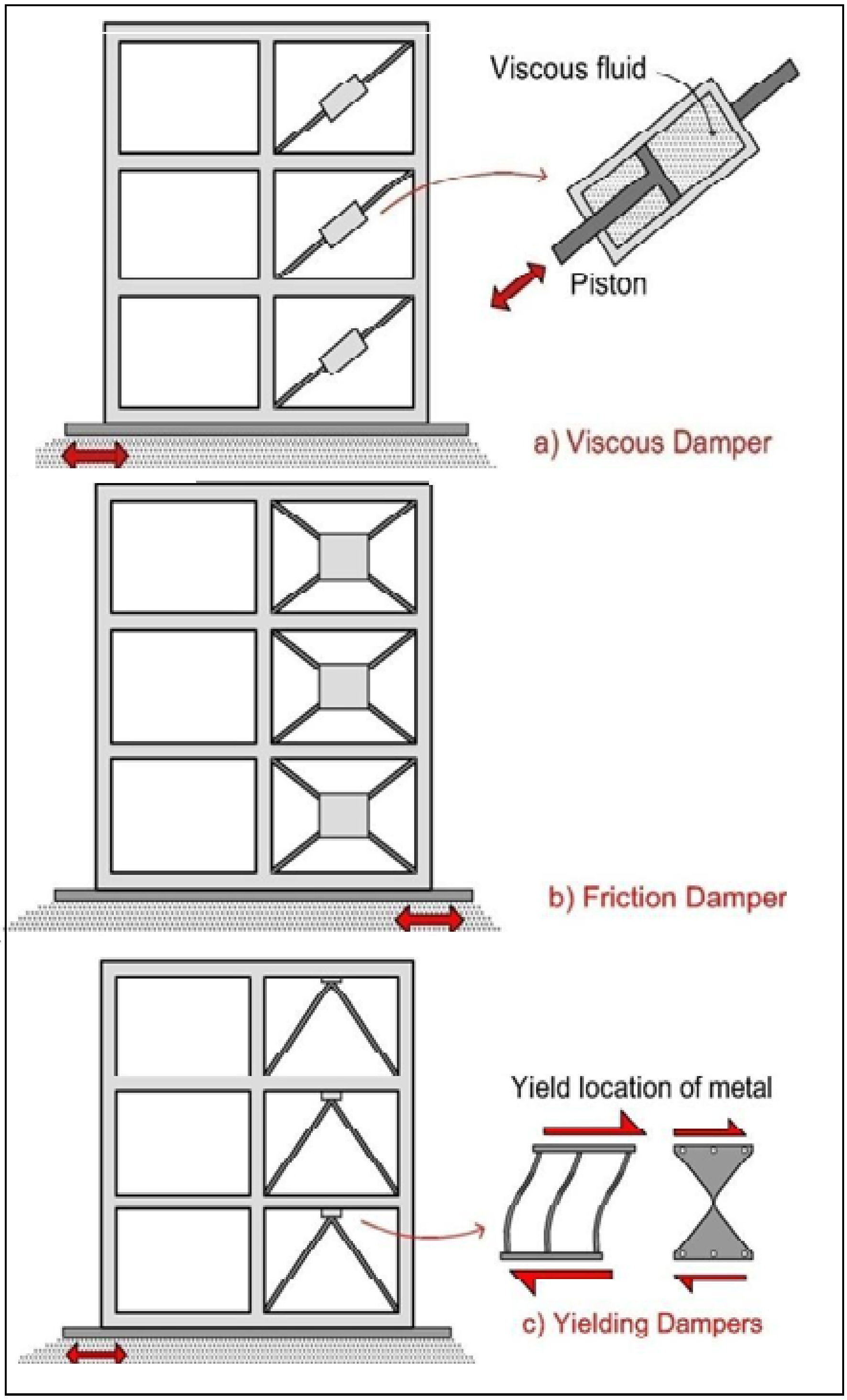
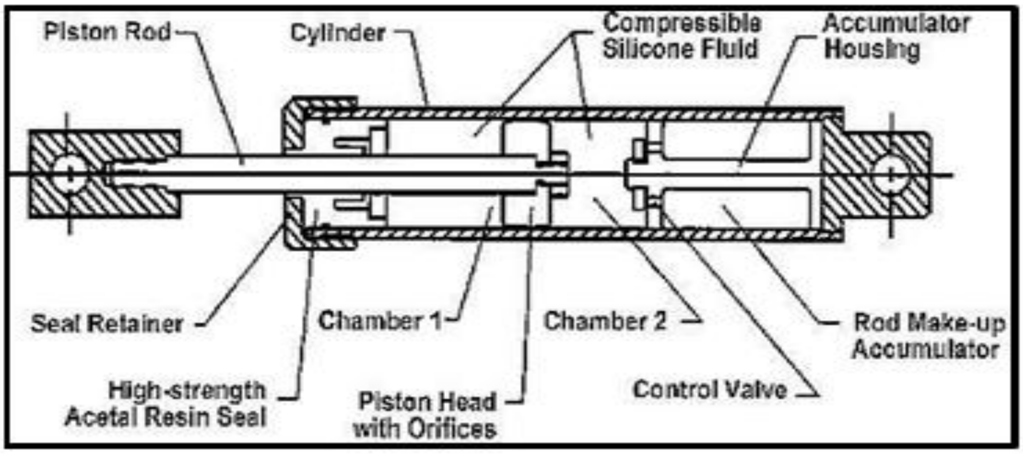


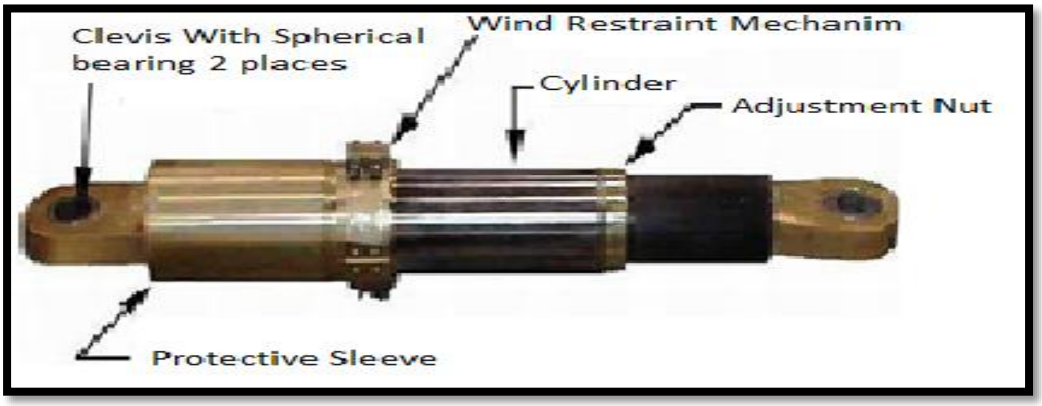
Figure 3.11. Dissipation devices [19].

Fluid Dampers

The structural configuration of fluid dampers is illustrated in Figure 3.12. A typical fluid damper consists of a steel piston and an opening head made up of bronze. This part is generally full of silicone oil. A piston head has specifically-designed passages to change the damper fluid flows, so, they offer useful features to change the damper resistance to the earthquake. A fluid damper works on the principle of clean energy dissipation. The shock-absorption structures installed in our cars, which serve as an example of fluid dampers.



(A) Schematic



(B) Photograph

Figure 3.12. Typical fluid viscous damper [19].

When dampers use viscous liquids, they are termed as viscous or fluid viscous dampers. They are illustrated in Figure 3.12 and they absorb energy through their compressed viscous fluids. Viscous dampers appear just like generally used shock-absorbers, which are installed in vehicles. Their piston shifts the seismic energy to the damper fluid that moves it within the structure of a damper. This fluidic movement releases kinetic energy and changes it into heat energy. For vehicles, it receives a shock from a damped wheel and does not let it shift to the body of a passenger.

When a structure has dampers, it will horizontally move to a lesser extent, thus, it will result in reducing the calamity. Since the earthquake sometimes has top force and velocity, which is too much for a structure and its earthquake-resistant devices to handle but a good damper does not let the structure collapse.

Another form of viscous dampers is lead-extrusion damper that makes use of solid lead rather than any viscous substance [48]. Experts have discussed lead extrusion dampers in details because protect buildings from maximum displacements and devastation. Specifically designed high force-to-volume (HF2V) lead-extrusion dampers were invented at the Canterbury University [49]. They are illustrated in Figure 3.13a.. They resist against seismic jolt when a shaft moves through lead as illustrated Figure 3.13b. This lead crystallizes again when deformation occurs but they decrease the chances of permanent displacement.

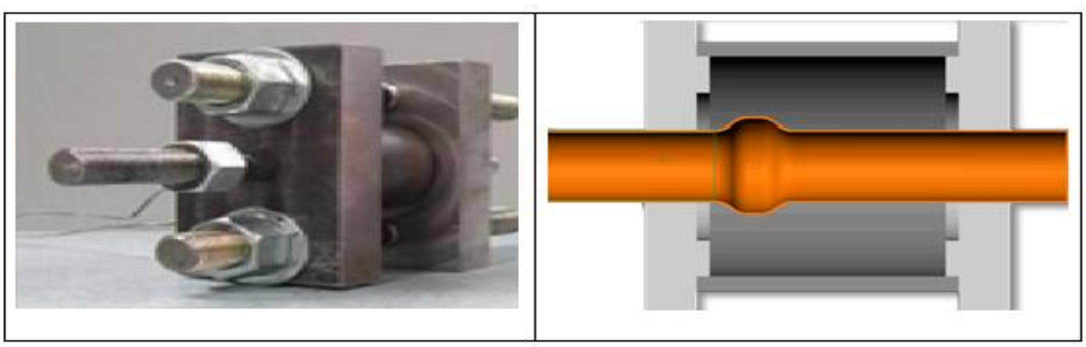


Figure 3.13. Lead extrusion damping device a) Size of The HF2Vdevice, b) Shaft with bulge that passe [49].

Friction Dampers

They utilize either a metallic or another surface to create friction and absorb energy within the surfaces, which have considerable friction between them when they rub each other. Generally, friction damper devices have a set of steel plates, which are placed to slide/move with each other in the opposite direction. Their function is obvious from the figure given below Figure 3.14. These dampers dissipate energy through friction that exists between multiple surfaces.

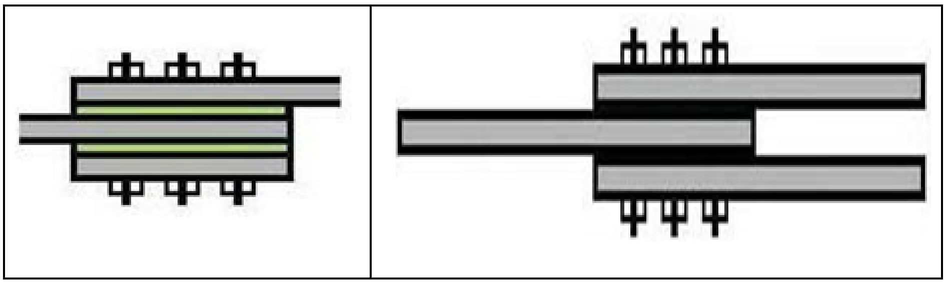


Figure 3.14. Steel plate arrangement in A friction damper [19].

Visco-Elastic Dampers

This is another damper type that consists of an elastomer and a mixture containing metallic substances. These dampers absorb energy through controlling the solid shear. These dampers combine two types of elements including the pure frictional and visco-elastic processes to dissipate the earthquake energy. They consist of a series of friction pads and polymers for visco-elasticity. They have steel plates and a pre-stressed bolt that moves with disk springs. They contain hard washers to maintain the required clamping force for creating friction-damping.

Hysteretic Dampers

It is another form of dampers, which help dissipating the seismic energy when an earthquake hits it. They are manufactured with the help of metallic parts to absorb energy through yielding deformation of the metal. Their parts are generally made up of steel. This type of dampers can bear bending, tension, and compression.

They consist of bendable u-shaped and triangular plates. They have the capacity to yielding steel across a specific length for avoiding excessive strains as well as less cyclical fatigue. The u-shaped plates are placed in such a way that they are narrowly spaced. Some devices deal with tension/compression because they are specifically manufactured for axial yielding; therefore, top lateral restraint levels are essential to protect against buckling during the compression process. Some steel tubes provide lateral restraint with the help of an epoxy or concrete filled in them.

Buckling Restrained Braces (BRBs)

These braces work just like hysteretic dampers as they dissipate energy through tension-compression braces, and they yield axial compression and tension with reverse cyclical loading. Buckling is actually a constraint that prevents steel components from functioning. Whenever BRB faces damages, it dissipates the displacement in length in order to protect against low-cycle fatigue failures.

3.1.11. The Performance of Base Isolation System

Now we will describe the results of different investigations conducted to assess the base-isolation performances of different buildings. We already know that the base-isolation systems help reducing the high loads. The knowledge obtained so far was collected after careful calculations and analyses by engineers and experts; however, some experts are skeptical about the isolation structures' performance in real-life seismic movement. A base-isolation system has been installed in the West Japan Postal Saving Computer Center. It performed very well during the Kobe earthquake, 1995[6].

3.1.12. Supplemental Damping Devices

They are extra devices, which are installed in different buildings to increase damping, which is in addition to the existing damping of the building. They help the survival of the building during earthquake because they absorb seismic energy and minimize the seismic response of a building. One good thing about these devices is that they work along with the existing base-isolation systems. placed in the diagonal resistant designs.

3.1.13. Base Isolation and Damping Devices

Different structures differently respond to earthquakes. Experts believe that when displacement increases in a building and that crosses a specific limit, a building bears damages in multiple ways and forms. It depends on how a building is constructed and what its earthquake-resistance mechanism is. For example, when a brittle building is erected and the designer expects it to elastically respond without ductility, it is possible to fail during the seismic movement because the ground exerts a severe force, which is more than that building's capacity to handle. Moreover, ductile structures also get damaged but somehow, it would handle an earthquake with less chances of failure. In this context, consider the following:

1. We have already discussed that some options are available, which help minimizing damage during an earthquake. These options are very helpful to reduce seismic vulnerability of the buildings.
2. Some equipments and construction techniques provide buildings with strong structures. This strength has a big cost in terms of the use of financial resources.
3. Buildings should be economical and yet earthquake-resistant because if the right strategies are applied, it provides seismic safety as well as economy. If an earthquake hits, the damage will be reduced and limited to only a few things.
4. In the areas with history of severe earthquakes and seismic lines underneath, buildings should be protected using external interference such as providing extra damping and strength to the existing buildings.

Some engineers and earthquake experts use traditional approaches to save buildings from seismic calamities. Their focus is only increasing a building's strength to avoid a possible collapse. This is an active procedure because it adds certain materials to a structure of a building but still, no one knows what would be the scale and intensity of an earthquake, so the element of uncertainty remains in the minds of building designers. Many experts recommend that the designers should construct ductile buildings to protect them against extreme jolts, which can cause a permanent damage to any structure.

Another possibility is conducting researches on damaged designs, which has become quite significant over the last 10 years. Different governments have developed a set of guidelines to minimum loss of life and property when large-scale deformation takes place. Some experts have found solutions to minimize losses in timber, concrete, and metallic structures, which will be discussed in the last parts of this thesis.

Another option is the external modification of a building for reducing its earthquake-response. This approach can be sub-divided in two forms:

1. Base-isolation to protect against the earthquake
2. Improving a structure's earthquake-resistance by using damping equipments to limit the building's earthquake response for decreasing damages.

It is possible to overlap both these forms as some damping equipments are feasible to install along with the base isolation, which improves a building's damage-resistance. A central aspect to event-based isolation strategy is its flexibility that it brings into action, and that does not let the building disintegration to take place. Moreover, isolators not only allow flexibility but absorb the earthquake jolt as well, which further increases the damping to a structure. Some base-isolators have appearances like rubber pads while others allow sliding. Experts believe that base-isolation does not suit every building. Some multi-storey buildings and structures constructed on soft soil are inappropriate for base-isolation. This technique is useful just for medium and small buildings constructed on hard soil [19].

3.1.14. Dynamics of Seismically Isolated Structures

A seismic construction, its acceleration and displacement spectra are shown in Figure 3.15. which illustrates the trade-off between horizontal displacements and horizontal accelerations in seismically isolated structures.

A seismic design spectrum plots the peak spectral acceleration or spectral displacement versus basic vibration period of a structure under expected earthquake ground motion excitation. Fundamental vibration periods for an isolated and fixed-base (or non-isolated) structure are shown clearly.

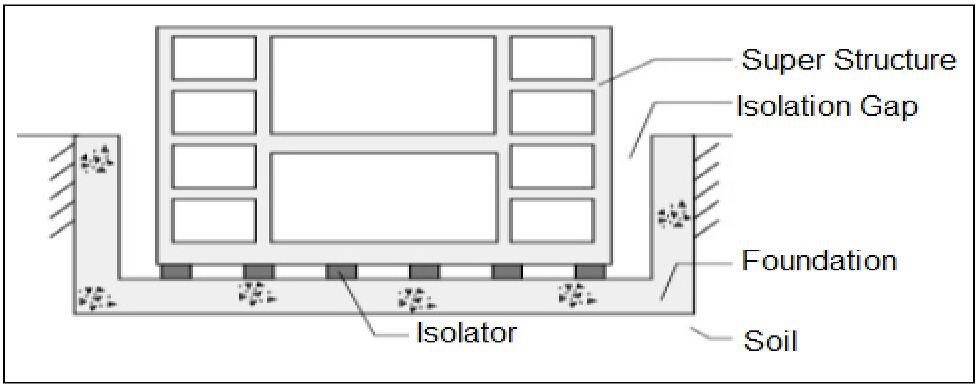


Figure 3.15. Components of A base isolated structure shown in elevation [50].

When basic vibration time of a building rises (structure becomes more flexible), horizontal accelerations are managed and therefore, the seismic inertial forces decrease. Simultaneously, horizontal displacements increase as the vibration period increases. These increased displacements of the isolated superstructure, however, are concentrated in the seismic isolation layer because it is much more flexible than the superstructure. These displacements are accommodated by providing enough space around the superstructure, a seismic isolation gap (Figure 3.16). to make it freely travel during an earthquake.

The deformation (the inter-storey drift) as well as horizontal flooring acceleration in a superstructure will be smaller than those in its fixed-base counterpart because the inertial force present in superstructures is much smaller. Efficacies of isolation systems is dependent on the isolators' ability to alter the basic structure's time period such that is larger as compared to that of non-isolated structures, inducing response that is far past the acceleration-sensitive region of the earthquake spectrum [51].

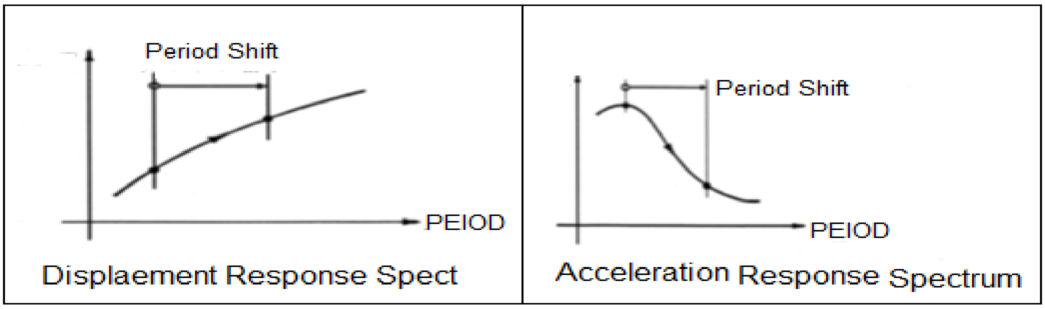


Figure 3.16. The effect of periodic elongation through seismic acceleration and acceleration and displacement of structure [50].

3.1.15. Steel-Plate/Concrete Modular Construction

Conventional fixed-based nuclear power plant structures are constructed using the reinforced concrete structural shear wall elements to form the primary gravity and lateral-load structural systems. In addition to their load-carrying ability, such walls offer good radiation protection, provide a satisfactory pressure barrier, and offer good fire resistance.

The isolated superstructure and the foundations of seismically isolated nuclear powerplants, which may also be constructed using this conventional technology. The structural reinforced concrete shear walls are erected using the cast-in-place construction method. The forms for such walls are erected first. The reinforcement is placed into the forms, usually using pre-assembled reinforcement cages.

Finally, the concrete is poured into the forms, vibrated into place, and left to cure a strength that allows removal of forms. While there is ample experience with such construction method in the industry, three obstacles still remain. One is the design of the forms to sustain the weight of the flowing concrete, which limits the height of the pouring lifts, thus constraining the speed of construction. Second is the time needed for concrete to cure to the level where forms can be removed to advance construction.

Use of slip-forming for cylindrical walls can accelerate construction. And third is the need to completely remove the forms such that, over time, wood debris left behind does not cause unwanted corrosion. Liner corrosion problems have been observed at existing U.S. nuclear plants left during the construction due to wood debris.

The solution to these construction problems is to use the so called “stay-in-place” forms. Such forms are, by themselves, structural elements that are capable of sustaining the load of flowing concrete and additional formwork above the pouring level. In addition, they canbe composited with the poured concrete to become part of the larger structural element.Stay-in-place such forms are, furthermore, pre-fabricated and pre-assembled into large modules, enabling significant speedup in construction.

The principal advantage of steel stay-in-place forms is that the form steel can be composited with the interior concrete to form a composite steel-concrete structural element sometimes called sandwich walls [51]. In addition, the isolation system modeling accurately reflects an isolator unit’s spatial distribution for transition in two horizontal directions. That must adequately show the aspects of different units within an isolation system. Normally, the base-isolation systems have non-linear behaviors rather than linear. Because of some situations, linear visco-elastic forces deform the relation, which is possible for isolation systems, and it is possible to conduct a simple analysis using stiffness values of K and damping of ξ.

The way an isolation system behaves is sometimes considered as linear if the given conditions apply:

1. An isolation system’s useful stiffness is not under 50% of total stiffness while the displacement remains $0.2d_{dc}$(d_{dc} implies an isolation system’s stiffness center).
2. The damping ratio remains less than or equal to 30% (because more damping value might result in coupling that increases floor-acceleration and foundational shear.
3. Force-displacement aspects of base-isolator changes by maximum 10% and not more than that because of the loading rate or vertical load.
4. The restoring force of an isolating system does not increase (displacements $0.5d_{dc}$to d_{dc}) above 2.5% of the total gravity load.

3.2. ISOLATION SYSTEM DESING

While evaluating horizontal stiffness values, the torsion motion on vertical axis might be neglected. In a simple and linear analysis when both are in a principal horizontal direction, the overall eccentricity between the isolation system's stiffness centre and superstructure mass' vertical projection is not more than 7.5% of the superstructure transverse length [52].

3.2.1. Model Design

In order to describe facts, a 40-storey model structure was taken. The model floors were made with 10mm thick steel plates having 35 x 50cm area. It was made earthquake resistant having two steel endplates and several thin steel shims used along with the rubber. It is exhibited in (Figure 3.17.). Steel shims are vertically stiff having no impact on the overall horizontal stiffness.

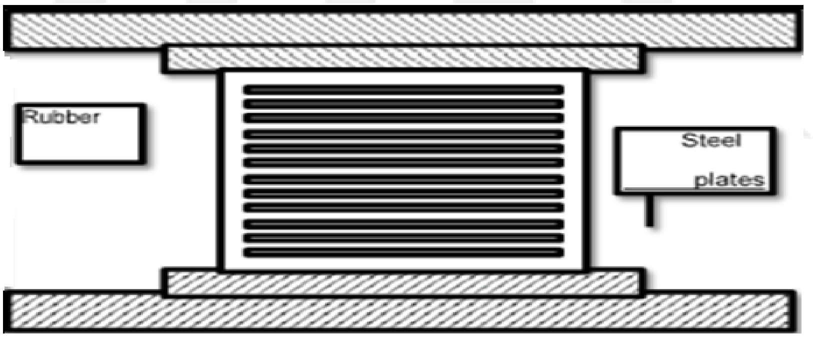


Figure 3.17. Isolation system using rubber steel base [41].

The horizontal stiffness is controlled through the elastomer's shear modulus. The shear material generally reaches shear strains by100% having damping range 2 to 3%. When this device is used, manufacturing isolators without damping is impossible that implies that isolators show linear shear behavior.

3.2.2. Characteristics of Well-Designed Seismic Isolation Systems

1. Flexibility for increasing vibration period that reduces response to force.
2. Dissipating energy for controlling displacement of an isolation system.

3. Rigid under small loads like low-scale earthquake and wind.

3.2.3. Major Components

1. Rubber Layers: Provide lateral flexibility with dimension L*H*W (1.0*1.0*1.0) meter.
2. Steel Shims: They assure vertical stiffness for supporting building load and limiting horizontal rubber bulging L*W*T (0.8*0.8*0.05) meter. Our system is high damping natural Rubber bearing.

3.2.4. High-Damping Natural Rubber Bearings

1. Highest shear strain = 200-350%.
2. Damping increases through extra-fine oils, black carbon, or resins.
3. Proprietary fillers.
4. Damping ratio = 10-20% having shear strain100%.
5. Shear modulus = 50-200psi.
6. The useful stiffness/damping depend on:
   a) Elastomers & fillers.
   b) Contact pressure.
   c) Loading velocity.
   d) Load history.
   e) Temperature range.

Table 3.1. Show the main differences between low and high damping natural.

propeties	Low Damping Natural	High Damping Natural
Damping ratio	2 to 3%	10 to 20%
Maximum shear strain	100%	200 to 350%
Manfucture methode	Simple to manufacture	Diffuclt tomanufacture
Model design	Easy to model	diffcult to model
Shear modulus	85 to 100	50 to 200psi

3.2.5. Configuration of Building Structure with Base Isolation System

We need to define the selected elastomeric isolators, which were engineered as per ISO 2007 standards. Every value that diameter assumes, thickness values can be calculated. It must be remembered that in common buildings, highest t_i values are very appropriate because of low vertical load (v) values. Hence, every pair $D - (t_i)$, and every rubber layer(n_g) number, the thickness of the rubber is illustrated in Figure 3.18:

$$t_i = n_g * t_i \tag{3.8}$$

For shear strain γ_s and maximum possible value γ_s:

$$\gamma_s = \frac{d2}{t_e} = \gamma_s\text{, lim} \tag{3.9}$$

In addition, by taking γs, lim = 2.0. Italian code [53], shows that we should deduce highest horizontal displacement during a specific earthquake will be:

$$d_2 = 2 * t_e. \tag{3.10}$$

When the highest value for bending rotation α is fixed, which is generally low, its concerned shear strain γα will be as follows:

$$\gamma_\alpha = \frac{3}{8} * \alpha * \frac{D_e^2}{t_i\, t_e}. \tag{3.11}$$

In this case, the highest shear strain value because of the vertical load will be:

$$\gamma_c = \gamma_t\text{,lim} - (\gamma s + \gamma\alpha). \tag{3.12}$$

Where we take $\gamma_t\ , lim\ =\ 5.0\ as\ per$ MinInfra-2009. Its vertical load will be:

$V_C = S_1 \cdot Gdin \cdot A_r \cdot \frac{\gamma_c}{1.5}$ that needs comparison with critical load

$$V_{cr} = S1 \cdot Gdin \cdot A_r \cdot \frac{D_e}{t_e}. \tag{3.13}$$

In addition, the vertical load for highest stress in steel plates will be:

$$V_{Lam} = f_{yk} \cdot \cdot \frac{A_r . t_s}{1.3.2 t_i}. \tag{3.14}$$

The highest load on the selected isolator, which is linked with displacement

d_2, is $V = min\ (V_C, V_C, V_{cr}, V_{Lam})$. (3.15)

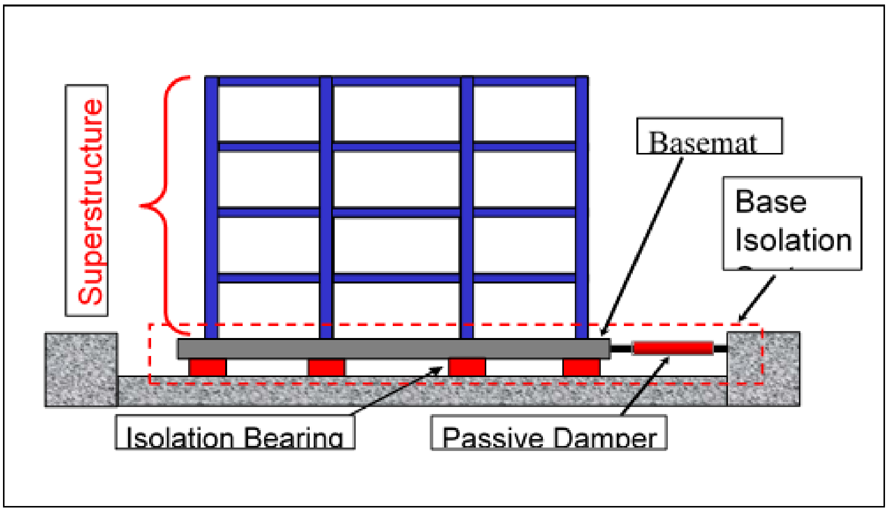


Figure 3.18. Basic elements of a base isolation system with dampers [54].

3.2.6. Real Seismic Isloation System with Passive Dampers

Japan has faced the earthquake issue more than most of the countries where the isolation application on structures of bridges has been limited because of spectral shapes according to bridge codes in Japan. Their construction over long periods is essential for achieving appropriate force-reduction; therefore, the period-shifting as well as flexibility do not come into action. In this case, the isolators are only used for dampening the response and redistributing the lateral load in a useful way among the substructures.

Moreover, isolation is useful in a longitudinal direction as its side-restraint helps preventing transverse-displacement on the isolating devices. The base-isolation provides safety during an earthquake, which is termed as "Menshin design" in Japan. This system has been provided in written form in the Highway Bridges Manual of Menshin Design and Kawashima and Unjoh (1994) has also discussed it.

Some building codes specifically allow base-isolation and dissipation of passive energy. They are enforced in countries like the United States, New Zealand, and the European countries. The US Uniform Building Code is perhaps has the most details [55].

Most of the codes apply to the new construction. The thinking behind it is that some isolated structures should outperform traditional construction during both medium and intense earthquakes [56]. The intention behind drafting these codes is urging builders to invest on damage control, increase in damping, and force-reduction of a building rather than reducing its cost of production.

The elastomeric bearing shown below was made according to the needs of ‘Tentative Seismic Isolation Design’ 1986, which was a very complicated procedure, and according to some experts, more tedious as compared to the 1986 documents Figure 3.19.

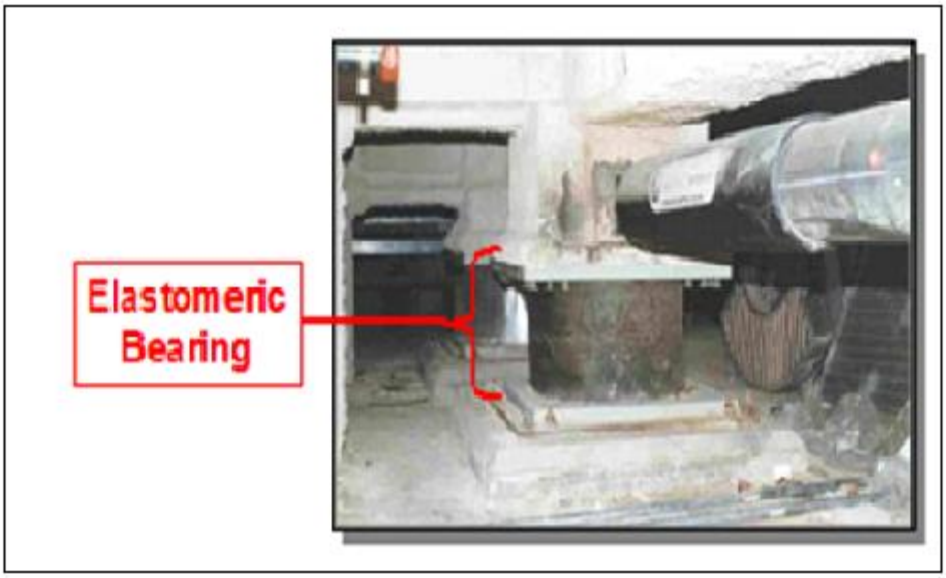


Figure 3.19. Elastomeric bearing along with supplemental fluid damper within an isolation system [54].

3.2.7. Application of Seismic Isolation to Retrofit Projects

1. Preservation of historic buildings with minimum alteration/destruction.
2. Maintaining functionality of structures even after seismic events.
3. Design economy (base-isolation is a financially viable and the most acceptable solution).
4. Protection of investment (reducing long-run economic losses).
5. Protection of content (The cost of contents present in a building can be higher than its structure).

3.2.8. Shear Deformation of Elastomeric Bearing

Bearings, which create base-isolation can be weak given the highly rigid shear that has minimum buckling load in comparison with traditional building elements. Consequently, including axial load is significant (particularly its P-A effect) for dynamic structural analysis, which supports elastomeric bearings. It is practically valid because base-isolation needs a lot of bearings for base-isolation.

To have a fair idea about the need for bearings, experts used 98 rubber bearings to protect the Foothill Communities Law and Justice Center in California, which was the first US earthquake-resistent building.

For avoiding large unit costs, bearings are ordered in standard sets. In that case, every bearing has a given capacity to bear high axial loads. Moreover, to handle massive earthquakes, bearings bear very high displacement, which may overturn a base-isolated structure that further raises axial load for bearings to handle. In order to dynamically analyze these possibilities because attention should be given to the P-A impact on the behavior of bearings.

The elastomeric isolation bearings are generally modeled using a Haringx column. It is shown in Figure.3.20. In this context, we should consider shear as well as flexural deformations because they are very important. To provide the foundation to Haringx's theory, axial load impact on the rubber bearings show stale and lateral stiffness that needs further analytical studies and continuous experimentation.

Recently, visco-elastic P-A model has been presented that emphasizes the use of elastomeric isolation bearings during the construction. Although it is a new model, it has accuracy and it decreases the significance of the Haringx theory, and its assumptions about the static form. Actually it is not a highly practical and easy-to-apply model, which has been used to conduct majority of structural and analytical projects. This was the reason of developing the simple mechanical model having two internal degrees of freedom that show the rigidity of shear and the bearing's flexural rigidity [57].

In the context of earthquake-resistent design, the Shear modulus G is the single most significant design property, which is also a method to explain the elastomer capacity. It is quite probable to have different equipment having a single elastomer but they will possess identical hardness levels and different shear modulus.

Irrespective of elements' shapes and sizes, which base on external load and elastomer layer properties within the contexts of varying loads and atmospheres, it is possible to detect different damages through the following factors:

1. Delamination/steel spliting/elastomer layer that result in maximum shear strength reduction.
2. The wear and tear of elastomer layer because of absence of necessary shear strength/design issues.
3. Elastomer layer crushing because of extreme loads or inappriate rotation.

When an elastomer ages and loses its design properties, some damages are detectable on the laminated composite and through other effects on the elements' general properties [58].

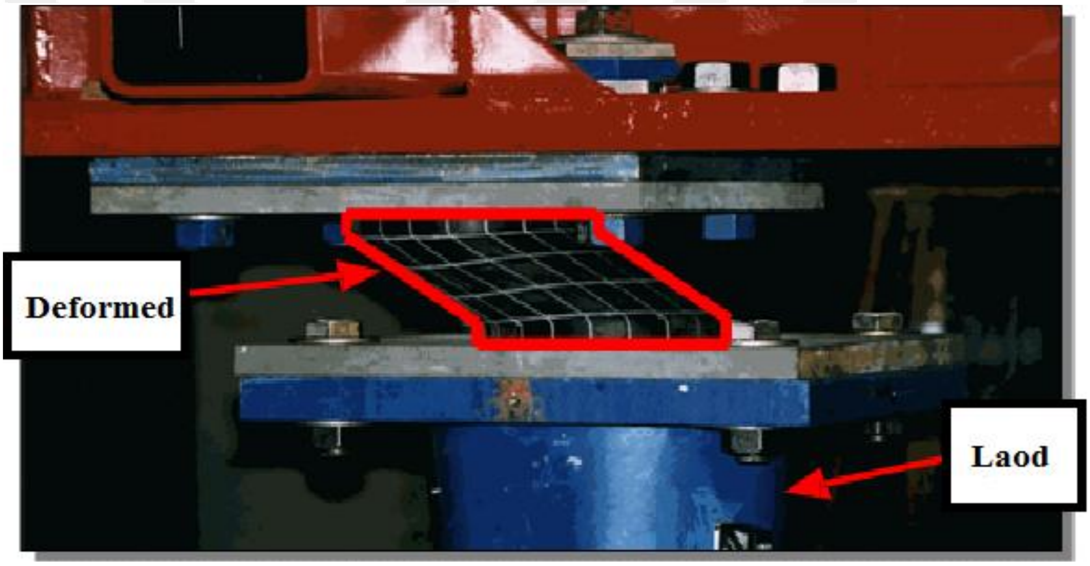


Figure 3.20. Shows shear deformation of elastomeric bearing [54].

3.2.8.1. Bearing Manufactured by Scougal Rubber Corporation

This report will describe the testing of six elastomeric bearing pads produced according to the needs of the clients by Scougal Rubber Corp. They are manufactured only for thermal expansion but the research work focuses on determining every pad's response if they are subjected to seismic loading. Many bridges have the needed base isolation, which is particularly framed for specific purposes and have more costs as compared to thermal expansion pads. It is very difficult to produce them because their producers have to fulfill very stringent requirements, and besides, they have higher weight.

An isolator's main weight is more because it consists of steel reinforcing plates for vertical stiffness in the form of rubber-steel combined elements. Generally, the rubber isolation is possible through installation of two big end-plates (25mm) and some 20 reinforcing plates having 3mm thicknesses. The isolators' excessive production costs are due to steel plates, sheets of rubber and molding/vulcanizing process. The manufacturers first cut, then sand-blast, then acid- clean, and finally coat the plates. Later, rubber sheets having inter-leaved steel plates are heated and molded for many hours for finishing their manufacturing. The current research suggests that it is possible to reduce the production costs and weights of isolators. This is possible when a manufacturer uses thin steel plates, no plates on ends, and zero-bonding production techniques. When the requirements will decrease and the production process will be simplified, the production cost will become lower.

The production of traditional isolators is performed with great care because following specific codes and meeting the testing require manufacturers to test their isolators before installing them to understand the load condition. Currently, a bond exists between steel and rubber, which helps materials to pass the tests. When the shear displacement is large enough, an isolator generates balanced reaction that needs to equalize through applying tensile stress. Compression loads create overlapping among upper and lower surfaces while tension and stress carries the unbalanced moment.

The thermally expandable bridge bearings have less costly as compared to other earthquake-resistant bearings. Their demand is low; however, their analyses show that in case they face seismic displacement, they might deform but they won't be damaged. A major reason behind this is that the upper and lower surfaces have the ability to roll off and they produce no tension stress. These unbalanced moment arms bear vertical loads by offsetting the upper and lower surface forces, which are illustrated in Figure 3.21 [59].

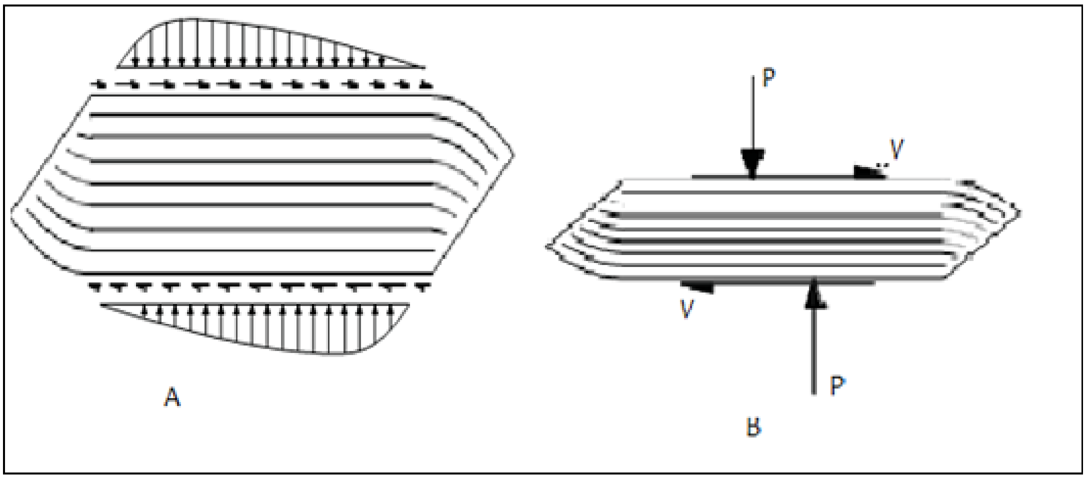


Figure 3.21. a) Distributions f normal and shear stress, b) Moment caused by the offsetting resultant compressive loads [56].

3.2.8.2. Harmonic Behavior of Elastomeric Bearing

The elastomers simply utilize a non-linear spring because the available damping devices are insufficient as the model is generally dependent on the amplitude. This leads to the development of a computationally effective and accurate elastomeric model that takes into account the information regarding the damping properties of a damping substance. We discussed earlier that the elastomer's elastic behavior generally interacts with rubber compounds and fillers in filled elastomeric substances.

As far as the physical process is concerned, an un-uniform distribution having rate-dependent elasto-sliding substances is utilized for emulating the behavior of the filler structure and a parallel linear spring, which represents the residual damping and stiffness. Many single-frequency and double-frequency tests were carried out to identify characterization of materials, model parameters and validation analysis because the mentioned material model is utilized for damping designs and it is possible to integrate them with dynamic systems' numerical analysis, which is illustrated in Figure 3.22 [60].

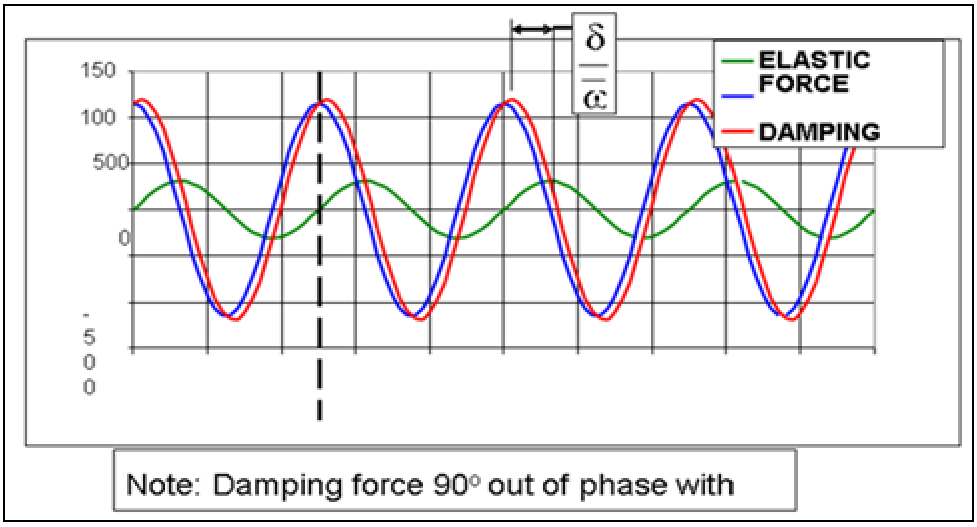


Figure 3.22. Harmonic behavior of elastomeric bearing [54].

$$\mu(t) = \mu_{(0)}\ (sin\ \bar{\omega} t) \tag{3.16}$$

$$P(t) = p_0 \sin(\bar{\omega} t) \cos(\delta) + p_0 \cos\bar{\omega}\, t \sin(\delta) \tag{3.17}$$

Where:

$\bar{\omega}$: loading Frequency.

$(\bar{\omega} t)$: Imposed Motion.

P(t): Total Force

δ: Phase Angle (lag).

3.2.8.3. Analysis and Design Methodology

Many efforts have been made to analyze Lead-rubber base-isolattion according to a process defined in UBC 1997. After that, many structural elements were design to handle appropriate loads according to the temrs and conditions laid in IS 456:2000, IS 875, and IS 1893.

Expets developed a 3D building model with the help of Asyns, which is a very popular among building designers. Computers and Structures Inc. deserves the credit for making it. The building models consist of some finite elements for making shear walls. The beams simulated the columns and isolators were represented like spring elements.The isolators have shear stiffness, which was considered while creating the model. External load was applied to the model in the form of 100% strain in a vertical direction. It makes possible the linear analyses of a structural response. It was found that the isolators' necessary damping factor ranges between 0.2 and 0.3.

This helped identifying the needed information to conduct a seismic structure analysis, which includes the layout of floors, parameters of loading, sizes of accessories and equipments including their material properties [61].

PART 4

METHODOLOGY

4.1. MATERIALS AND METHODS

4.1.1. Base Isolation System

4.1.1.1. AISI 1018 Mild/Low Carbon Steel

AISI 1018 mild/low carbon steel has excellent weldability and produces a uniform and harder case. AISI 1018 mild/low carbon steel offers a good balance of toughness, strength and ductility. Provided with higher mechanical properties, AISI 1018 hot rolled steel also includes improved machining characteristics and Brinell hardness. Specific manufacturing controls are used for surface preparation, chemical composition, rolling and heating processes. All these processes develop a high quality product that is suited to fabrication processes such as welding, forging, drilling, machining, cold drawing and heat treating (Properties of Low Carbon Steel with Various Microalloying Additions after Particular .

Table 4.1. Properties of AISI 1018 Mild/Low carbon steel.

Mechanical Properties	Metric
Hardness, Brinell	126
Hardness, Knoop (converted from Brinell hardness)	145
Hardness, Rockwell B (converted from Brinell hardness)	71
Hardness, Vickers (converted from Brinell hardness)	131
Tensile Strength, ultimate	440 MPa
Tensile Strength, yield	370 MPa
Elongation at Break (in 50 mm)	15.0 %
Reduction of Area	40.0%
Modulus of Elasticity (typical for steel)	205 GPa
Bulk Modulus (typical for steel)	140 GPa
Poissons Ratio (typical For steel)	0.290
Machinability (based on AISI 1212 steel. as 100% machinability)	70%
Shear Modulus (typical for steel)	80.0 GPa

4.1.1.2. Mechanical Properties of Rubber

Because of its high elasticity and strength, a natural rubber is the basic constituent of many products used in the transportation industry, consumer, hygiene and medical sectors. In order to develop new rubber materials for more applications, investigation of their mechanical and thermomechanical properties in various conditions are required. The effects of thermomechanical couplings in solids often occur in nature. In general, by thermomechanical coupling, we mean “strong” or “weak” interactions between mechanical and thermal effects.

Table 4.2. Properties of the rubber.

$G(MN/m^2)$	0.85
$E\psi(MN/m^2)$	2030
ε_b	6
Hardness (IRHD)	40
x	0.85

4.1.1.3. Mechanical Properties of Base Isolation System

The mechanical properties of an elastomeric bearing in all degrees of freedom are integrated using a physical model presenting physical models of circular and square bearings, which use complex arrangements of shear and axial springs to simulate stability and shear effects under varying vertical loads.

Due to the mechanical properties of rubber bearings, tension forces in a rubber bearing (a result of overturning moment) and vertical seismic force must be suppressed in the design of a seismic isolation system. Since the building weight is concentrated into the large square LRBs, the uplift force caused by the overturning moment is theoretically minimized. The large square LRBs are always under compression stress, even when considering the coupling effect of overturning caused by horizontal earthquake forces and uplift effects caused by vertical earthquake forces.

Table 4.3. Properties of the laminated rubber bearings.

Rated Vertical Load (MN)	4.9
Horizontal Natural Frequency (Hz)	0.5
Vertical Natural Frequency (Hz)	19.8
Horizontal Stiffness (MN/m)	4.8
Vertical Stiffness (MN/m)	7700
Allowed range of horizontal deformation (m)	0.50

In addition, the stiffness is linearly distributed; the base building is rigidly attached to the ground, whereas it is retrofitted with the proposed hybrid isolation system in the boundary conditions. The 40 storeys are free and the displacement of the base is 1.5 mm.

Moreover, base-isolation helps to overcome the devastating effects of an earthquake because it sustains a structure's natural period for a long time, such as from 2 to 4 seconds, with the help of laterally flexible isolation equipment on a structural foundation that practically decouples and frees its foundations from the soil underneath. In order to deal with the earthquake excitation, period reduction also helps by lowering the acceleration of a floor and by controlling the inter-story drift by a super-structure, which exists above the foundation. Both practical situations and comparisons show that the base-isolated buildings perform much better compared to their non-isolated counterparts. This helps to make the superstructure more elastic, thereby saving it from an immediate collapse. In addition, lowered demands reduce the possibility of a disaster and improve safety by dealing with displacement. This periodic shift does not allow the displacement to increase and it can be managed using the base-isolation equipment mentioned previously. When the acceleration is reduced and drift demands are lowered simultaneously, it becomes a useful operational strategy against a devastating earthquake. This situation gives rise to a potential question: Is it possible for structural engineers to produce and present financially viable designs of new structures with the lowest possibility of a structural devastation? The answer is that in the current scenario, experts mostly rely on two well recognized strategies to limit damage of an earthquake, which provides safety to life, property and objects present in buildings. These methods include improvement of strength and stiffness as well as energy dissipation, which helps to reduce damage.

For earthquake disaster risk reduction, we consider the following:

1. A simple and conventional technique to limit the damage during a devastating earthquake is "overdesign," which means a building will not disintegrate during an earthquake. This is possible through improving the strength level of a design and the attainment of structural stiffness in excess of the general levels for resistance against even the most violent earthquakes. This will keep a structure elastic during an earthquake; however, it will still require ductility to prevent a total collapse during major seismic activity. The mentioned overdesign is a possible economic solution for the safety of small buildings and few-storey houses, but not for very large, multi-storey structures. If measures were taken

to solidify multi-storey buildings and major halls/hotels, it would be too expensive as well as impossible to afford.

2. Base-isolation is an effective damage-control mechanism during a severe earthquake because it minimizes a building's response and isolates the building from the moving ground. This is possible through the installation of base-isolation equipment, including lead-rubber bearings, which were successfully installed in the earthquake-resistant Christchurch Women's Hospital. They have also been placed under buildings such as Te Papa, and the Wellington Parliament Building. They are financially viable buildings for construction but their foundations are pricier, and their overall cost is slightly above the cost of a conventional building. Moreover, they need to be completely operational so as to minimize the effects of major earthquakes [19].

4.1.2. History of Steel and Rubber in the Isolation System

The technique of base-isolation is introduced into the foundation of a structure that minimizes the effect of earthquakes on it. A horizontal surface adds to the damping devices and this restricts the amplitude of an earthquake. The actual idea of isolating a building from the devastating impact of an earthquake is not a new idea. The first patent regarding base-isolation was registered in 1909, and since then, many studies have been performed.

During the previous 20 years, a number of buildings were constructed using these principles, experts of which have been mentioned in their studies, books and writings. This gives an altogether new light to the concept of seismic isolation. It occurred through the invention of mechanical energy dissipaters and elastomers, which provided the necessary damping to the buildings. The application of mechanical energy dissipaters combines with the concept of devices providing flexible isolation, which limits a building's response to high displacement and deteriorating loads, thereby providing highly considerable earthquake protection.

The researched methods help to dissipate the seismic energy through equipment installation that is particularly helpful to meet the needs of the occupants of a building, including specially designed columns and beams which dissipate seismic energy and the capacity of seismic energy to disintegrate a building. So far, more than 200 buildings, in which seismic isolation principles are applied, have been erected.

In 1969 in a school located in Skopje, Yugoslavia, experiments were first performed on a rubber-based system that would provide resistance against seismic activity. Another such structure was built for Pestalozzi School, where a 3-storey structure was erected with the help of concrete using the expertise of Swiss engineers. An isolating mechanism called Swiss Full Base Isolation-3D (FBI-3D) was used. This mechanism differed from the latest rubber bearing systems which were generally fully unreinforced to manage the mass of a structure.

During an experiment, glass blocks were used. These glass blocks acted like fuses and broke down whenever an earthquake reached a specific intensity. Since the system has almost the same vertical and horizontal stiffness levels, a structure is likely to bounce back and forth during a seismic incident. This type of bearing was manufactured using reinforcing rubber blocks along with steel plates. The bridge bearings are not very developed and they are therefore unlikely to be used again. Recently, a number of buildings have appeared using multi-layered laminated rubber bearings along with steel reinforcement to bear the structural load. Since the system contains reinforced steel plates, the bearings are normally vertically stiff but horizontally soft, which creates a reliable isolation factor. Normally manufacturing them is easier because they are stationary bearings and therefore do not experience wear and tear over time and with environmental impact.

A number of specifically designed isolation systems have been utilized in high seismic risk countries such as Japan and New Zealand, where low-damping rubber bearings are installed with mechanical dampers. For the most part, they are hydraulic dampers and the bearing consists of steel rods, metallic coils and lead plugs. Experts have pointed out that using dampers is not without disadvantages, the first of which is that all dampers except for internal lead plugs need mechanical connections as well as regular maintenance. Metallic dampers have a non-linear yield and this increases the complications while analyzing it.

Lead-plug rubber bearings are commonly used isolation systems in the US due to the bearings having many layers and being elastomeric with round holes. When a lead plug is put into one of the holes, it adds damping. In some cases, a building would only have lead plugs while in others, multi-layered elastomeric bearings would be used with no lead plug.

Incorporating extra damping to an already performing system is quite possible by improving the elastomeric damping. Some US, Italian, Indonesian, Japanese and Chinese structures are isolated with the help of high-damping natural rubber bearings, and since it is a simple technique, it is more likely to develop further.

4.1.3. The Advantages of Seismic Isolation

Base isolation and its benefits should be considered while retrofitting an already built structure. For instance, the expenses of retrofitting a building are generally $5000 per square meter. Base-isolation reduces or ends the need of funds for strengthening a superstructure because it is a low-cost solution in comparison with other devices used for the same purpose. In order to save heritage, base-isolation has excellent advantages, thereby making it a viable option.

With some extra effort, a new timeline is required to accomplish a project. Profits are reduced and the design team does not receive the appropriate compensation for its efforts. This negatively affects design professionals and their teams who provide their time and focus on a project for the installation of the latest technologies; such installatyions require great efforts. As a result, the owners of buildings should properly compensate those who put in efforts to make a building earthquake-resistant. In practical terms, owners of buildings should take extraordinary measures, including base-isolation, if they wish to mitigate earthquakes and opt for safety over profit. Experts believe that base-isolation is in fact a precautionary measure to protect a building against the devastation of an earthquake. Even insurance covers only a part of the total possible damages and it does not guarantee risk reduction in cases of costly damage [62].

The following are major advantages:

1. Base-isolation significantly eliminates both structural and non-structural losses, thereby improving a building's safety and helping to save its accessories and architecture by reducing the impact of an earthquake.

2. Some rigid buildings are deeply ingrained in the earth, which makes them vulnerable. They include small and mid-sized buildings, nuclear plants, power generation plants, bridges and manufacturing plants, all of which require base-isolation to protect against devastating earthquakes.

4.3.1.1. Advantages of Sliding Types of Bearing

A great benefit of an isolator is its capability of changing certain variables such as its damping, natural period and displacement in order to protect a building against an earthquake by avoiding ground resonance. This type of base isolator possesses remarkable attributes, which are significant and adjustable in comparison with other base isolators used in regular engineering projects. Engineers who implement earthquake-protection projects focus on optimizing isolators on multiple earthquake intensities through the appropriate force of friction and curvature.

4.3.1.2. Advantages of Rolling Types of Bearing

In order to improve damping using a roller bearing and to increase a bearing's useful life, experts use a specific isolation system termed a static-dynamic interchangeable ball pendulum system (SDIBPS). This system comprises two concave spherical surfaces and a ball made from steel. This steel ball has a damping material on it to provide extra damping and to avoid damage such as scratches on the concave surfaces, which is helpful when an earthquake occurs. This system is sometimes constructed using many smaller steel balls, and these support a building's mass and protect it against any deforming action or damage to the damping material surrounding the steel rolling ball during the long term of service loadings. A damping substance covers the steel ball to protect it from scratches and save the concave surface which can be of any geometric shape including conical or spherical with different radii. Natural periods of SDIBPS isolators are dependent on the curvature radii of both the concave surfaces; however, it does not rely on the vertical load. It is possible to design it to make it depend on isolator displacement, which is both manageable and predictable [63].

4.3.1.3. Advantages of Friction Pendulum Bearings

The advantages of this type of system for base isolation are practically identified and approved in this thesis through analytical and experimental analysis. A numerical model of real reinforced concrete structures is defined and verified by comparing them with the experimentally measured results. The same model was used for the analysis of base isolated structures with a system of friction pendulum bearings in the base and a comparison of the results of these two analytical models was performed. The investigation was carried out in two phases:

1. Phase – Basic theoretical concept analysis for modeling the behavior of isolated structures.
2. Phase – Application of the proposed methodology for analysis of seismic isolated structures [64].

A major benefit of vibration control systems is the possibility to omit the traditional base-isolation during the construction of the foundation of a structure. In this case, the first storey has to play the role of the base-isolator. This is possible through the installation of passive friction dampers on the floor of the first storey.

A study has shown that the frame controls vibration and this is also evident from previous research. Taking this approach, an engineer divides the first storey into two parts. The first part has columns and the second part consists of passive friction dampers. The dampers are installed on the column sides and bottoms, which is very significant for resistance against violent seismic activity. Generally, the first storey performs as a base-isolator which helps to increase the frame’s natural period. Many numerical analyses show that the system actually contributes to overall safety, which means that it decreases shear force, reduces the inter-story drift angle, and controls earthquake energy emerging through tremors in the ground. A frame that has passive friction dampers is less likely to deform.

4.3.1.4. Steel Reinforced Elastomeric Bearings

The shear deformational characteristics of rubber limit its load carrying capacity as the thickness of the elastomer increases. As depicted in Figure 2.1, steel laminates are typically used to control bulging in the elastomer. The steel shims produce independent layers of the elastomer resulting in shearing of the individual layers relative to each other through the depth of the bearing. The end product appears in the shape of an alternating steel layer series and elastomeric that results in a vertically stiff and horizontally flexible bearing, thereby accommodating bridge movements without inducing significant horizontal loads to the substructure. An elastomeric cover is included on the outside of the steel plates to ensure protection from the environment.

4.3.1.5. Advantages of Steel Reinforced Elastomeric Bearings (SREBs)

SREBs have many potential advantages compared to other types of bearings, including the following:

1. Steel reinforced elastomeric bearings can provide flexibility in longitudinal and lateral directions for bridge girders while still maintaining the necessary stiffness in the vertical direction to safely support large girder reactions.
2. Horizontal stiffness remains relatively constant over the design life as opposed to PTFE surfaces, where debris or other corrosive action on the sliding surfaces can increase frictional resistance over time.
3. Steel reinforced elastomeric bearings allow short-term over-rotations with relatively low probability of damage [65].
4. Steel reinforced elastomeric bearings are an economically efficient alternative for the accommodation of bridge movements due to temperature and vehicular use both from an initial installation perspective and also from a maintenance perspective. There are many advantages of using elastomeric bearings, which

potentially makes the use of bearings in higher demand applications particularly attractive.

4.3.1.6. Shortcomings of Steel Reinforced Elastomeric Bearings (SREBs)

Despite the advantages of elastomeric bearings, there are also potential shortcomings of the SREB design:

1. SREBs may be more limited to supporting lower vertical loads than their design alternatives.
2. The rotational limits of steel reinforced elastomeric bearings are lower than the rotational capacities of many other types of bearing.

Properties

Different substances have different engineering properties. The substances utilized to produce bridge bearings need to have specific established properties before use. In the following subsections, we present the key criteria along with a brief discussion about their impact on the behavior of a bearing [66].

4.1.4. Technical Benefits of Base Isolation

Although many articles have been written on the technologies pertaining to base-isolation over the last three decades, it is unclear as to what would be its technical advantages for either bridges or buildings.

4.1.4.1. Benefits of Building Applications

1. They decrease the elastic base-shear, which a structure should resist according to factor range 3-7 and which also relies on the building period, type of soil underneath, earthquake magnitude and irregularity/fault in the design. When base-shear is significantly decreased, it also helps engineers to end or reduce the ductility demand that might cause damage to a structure.

2. Technically, there should be a stiff structure on a base-isolator with minimum or next to no amplification. Fixed base buildings increase the seismic acceleration by a factor ranging from 2.5 to 4, which again depends on the structure. If we compare forces on the ceiling, a base-isolator system provides a reduction factor ranging from 8 to 12 in comparison to buildings with fixed foundations. For example, two 6-storey reinforced concrete buildings experienced earthquake jolts in the 1995 Kobe earthquake in Japan. The electric, electronic and mechanical devices present in the buildings were generally sensitive to floor acceleration during a seismic movement. They included elevation systems, sprinklers and ceiling and electric lighting systems. To reduce the magnitude of floor acceleration, we use base isolation that improves the safety of the mentioned electrical, mechanical and electronic equipment in a building.
3. When base-shear and floor acceleration are decreased, experts have proven that inter-storey drift also decreases by a factor of 4 to 8. Normally windows, partitions, structural frames, duct work, facades and pipes are more vulnerable to high inter-storey drift during an earthquake. To decrease inter-storey drift magnitude, base-isolation is required, which ensures the safety of these important building accessories.
4. In fact a structure costs roughly one-fifth of the overall building cost whereas the remaining four-fifths (80%) are used to construct an exterior façade, architectural elements and technological components. When we are willing to produce an earthquake-resistant design, the designer will naturally focus on the structure to ensure safety of life, property, accessories and possessions. Generally, building designers perform poorly as far as seismic protection is concerned, which is indeed a valuable investment as it protects 80 percent of the overall building investment. It is evident from history that the elements most damaged were non-structural ones; therefore, engineers and designers should prefer the earthquake safety of these items and accessories as it can minimize or prevent any economic loss. Designers and engineers operating in areas with regular seismic activity should pay more attention here because in those areas, vulnerability is very high, and after an earthquake, economic costs of repair become very high.

5. In Point 2, we discussed the cancelation reduction of top floors during a seismic activity. In fact, it should be a topic of debate among the designer community because structural engineers have paid no sufficient attention on it through design perspectives. When the benefits of different isolating frameworks are clear, their attention should be focused on floors. Some friction-based systems show substantial force reversal. The elastomeric systems reduce high frequencies in the floors; therefore, when costs are compared, experts should focus on performance differences as a significant factor. They should also assure better safety for acceleration-sensitive components.

4.1.4.2. Benefits of Bridge Applications

1. Technically, a bridge has to have low elastic base shear and it should resist it by a factor ranging from 3 to 7. This fully depends on the bridge period, the type of soil underneath, the earthquake magnitude and the possibility of a fault. When the base-shear significantly reduces, it helps engineers to implement ductility demand elimination, which reduces any possible damage. Some latest bridge applications have emerged as cutting edge possibilities because they show remarkable cost reduction while laying the foundation for the system as they make use of the base-isolation technique. In the context of performance-based design, base-isolation helps designers to produce a good operational design with no cost increases if we compare it with traditional fixed base designs.
2. To retrofit applications in bridges, technicians need only replace the common bearings with isolating bearings as they reduce the seismic force. This can save on the cost of even strengthening the foundation and the columns.
3. Some isolating systems have a design aspect, which is their distribution capacity to manage horizontal loads of substructures. They therefore not only reduce the seismic load but also save weak substructures from disintegration. These design features are part of retrofitting applications for buildings. However, some of them also have serious potential for bridge retrofitting [67].

4.1.5. Advantages of Lead and High-Rubber Bearings

The significant benefit of lead-rubber bearings is the possibility of its combination with the rigidity function on high loads. Lead-rubber bearings are flexible during earthquakes and provide the required damping with a single installable unit. All this gives significance to lead-rubber bearings, which are currently the most commonly used isolators to meet the requirement of damping in active seismic areas and also for those buildings and bridges with a need for rigidity.

As far as HDR bearings are concerned, the formulae for elastomeric bearings also apply to the LRB designs. A building that has an installation of sliding bearings dislocates from its original position when a seismic movement occurs. During the aftershocks, the process of further dissociation continues. In order to overcome such problems, scientists have developed friction pendulum systems (FPSs) that shape a surface to slide in spherical form, thereby helping to deal with the dissociation issue.
When a bearing horizontally shifts, it will be vertically lifted, which creates a restoration force. FPS development turns a sliding bearing into a spherical surface, and this helps the structure to restore back to its genuine position because of vertical lifting. Scrap rubber tire can also be used for base isolation. There is a very large amount of friction between the two tire pads so it can adhere to both the tires. Although there may be some slippage between the tire, it is still helpful in the dissipation of energy. Some layers are rectangular in shape and cut out of the tread section of used tires. They are later piled on each other to create a scrap tire pad with the capacity to act as an elastomeric pad [63].

4.1.6. Disadvantages of the Base Isolation System

The major disadvantage is that the installation of a base-isolation system is normally very tedious. Moreover, the cost of the base isolation is so high that it can not be used in normal residential buildings. Generally, it can be adopted in some special buildings, such as government buildings, hospitals, schools and colleges.

If an earthquake occurs, vibration starts. If a base isolation is provided beneath a structure or building to absorb the shock of the earthquake, the building will be safe from earthquakes. In India, technical and research institutes exist in nearly all parts of the country; however, there is little research into base isolation. In Bhuj after the 26 January 2001 earthquake, every structure was constructed using base isolators. Because Bhuj is in an earthquake-prone zone, high magnitude and high intensity earthquakes occur frequently. Therefore, some necessary precautions must be taken to prevent damage. We can not provide earthquake proof buildings because of high costs; however, we are able to produce earthquake resistant buildings using the base isolation method.

The lead rubber bearing is used as a base isolation material in Bhuj after the 2001 earthquake. Lead-rubber bearings are generally composed of lead-plug force-fitting with a hole that is apparent in elastomeric bearings. The core is composed of lead, which is a source of rigidity to bear service loads and it dissipates energy despite its high horizontal load. In cases of strong winds and medium or low-intensity earthquakes, horizontal loads are lower and a lead-rubber bearing shows vertical and horizontal stiffness. Horizontal stiffness is a positive outcome of a lead plug, and it provides vertical rigidity that is the outcome of a steel-rubber bearing.

Normally on severe load levels, the yield of lead increases while the bearing's horizontal stiffness remarkably decreases. This creates a periodic shift in the base-isolation characteristics. When a bearing experiences cyclical and high displacement, which occurs in medium and severe seismic movements, the lead deforms and sucks the devastating energy through a process known as hysteric damping. This viscous/hysteric damping is a displacement function that normally ranges between 15% and 35% [68].

4.1.7. Features of Steel and Rubber

The characteristics of possible earthquakes include their period and severity. Subsequently, performance levels for different intensities of earthquakes need to be evaluated. Since the isolators carry large vertical loads and deform to a significant lateral displacement, the components of the structures above and below the isolator need to be designed appropriately. The plane of isolation may be selected based on the practical aspects of installation and the relative strengths of the super- and sub-structural components. Specifically, for the isolation system to work properly, the structure should be free to move in any direction above the maximum specified displacement.

Typically, a seismic moat is provided around the structure to allow for this movement. It is imperative that owners and occupiers of seismically isolated structures are aware of the functional importance of a seismic gap and the need for this space to be left clear. To maintain the structural functionality of a building immediately following an earthquake, every facility, electrical system and all sewerage pipes are to be specially designed to bear high earthquake displacement.

The main connections between the building and the ground, such as the stairs, entryways and elevators, need to be unconnected across the isolation plane. In general, every interaction between the structure and the ground needs to be designed and detailed. Seismic isolation provides immediate occupancy performance levels following strong events. The costs and benefits of different approaches may be evaluated to determine the incorporation of seismic isolation. In summary, there is a need for an effective isolation system that depends on the performance of the following factors:

1. Flexibility
2. Damping
3. Load resistance

Further requirements for mitigation of seismic incidents include cost effectiveness, ease of installation, and durability, which affects the decision of device selection. However, experts agree that earthquake resistance systems should have all these characteristics for effectiveness.

Researchers have introduced several isolation systems that are currently at different stages of development. Some of these developments have no practical significance as they exist only as concepts, whereas others have already become part of installed projects [68].

Normally, rubber bearings are made in horizontal layers. They consist of natural or synthetic rubber arranged in the form of thin layers joining steel plates that prevent the expansion of the rubber layers. In this case, a bearing supports a high vertical load with a minor deflection (generally 1 to 3 mm). Structurally, the inner steel layers have no restriction on the horizontal deformation of any rubber layer; so in this case, bearings scan how higher flexibility because of the horizontal load as compared to the vertical load. Therefore, a bearing operates as a flexible component.
Some properties of rubber isolators have been discussed previously. An isolating mechanism operates based on a principle that a stiff mass needs to be separated with the help of a flexible system. It is possible to isolate optimally a structure using rubber bearing isolators, which depends on static/dynamic properties and which can be proven in a lab. For these reasons, it is essential to understand the characteristics of rubber isolators for precise vibration analyses.

4.1.7.1. Durability Under Cyclic Loading

Under cyclic loads, rubber bearings generally remain stable. After several tests, the rubber isolators demonstrated that they remained stable even during an actual earthquake. Figure 15 shows the general friction factor against the cyclical loads on rubber isolators. It shows that the rubber isolators have sufficient durability. Rubber bearings are generally available in two forms: as LRBs or lead rubber bearings and as HDRBs. As a rule, elastomeric bearings have minimum damping, but steel plates are alternatively adjusted while a lead cylinder plug fits inside the hole.

LRBs were first invented and tested in 1975 in New Zealand. Afterwards, they were extensively used in the US, New Zealand and Japan. The steel plates of LRBs exert a bearing force that deforms the steel plate. It has an elastic restoration force that helps it to be restored after a seismic movement. However, the appropriately sized lead plug is required, thereby providing the necessary damping. LRBs reliably maintain their performances even when earthquake jolts are strong and occurring repetitively.

Basic Functions of LRB

1. Load supporting function: The rubber, which is reinforced using steel plates, helps to stabilize a structure. The rubbers should be multi-layered because they are vertically more rigid in order to support a structure as compared to single-layered rubbers.
2. Lateral elasticity function: LRBs help to convert the seismic vibration into low-speed movement. Since the lateral stiffness of multi-layered LRBs is lower, it reduces strong seismic vibrations and increases a structure's oscillation period.
3. Restoration function: The lateral elasticity LRBs brings a structure back to its real point of construction after a devastating earthquake. LRBs restore force in the rubber layers, thereby restoringtheir force. This restoration force brings the structure back to its genuine location.
4. Damping function: This is a source of essential damping. LRBs are available in two forms, one of which is traditional and round and the other squarish. Since the basic function has to be the same, shape change is beneficial on a number of occasions when builders are concerned about building costs, size, capacity and stability.

A high damping rubber bearing (HDRB) is a type of elastomeric bearing consisting of thin layers of high damping rubber and steel plates built in alternate layers. A bearing's vertical stiffness is normally a few hundred times that of its lateral stiffness, which is so because of steel plates. A bearing's lateral stiffness is generally managed using low-shear modes of elastomers. On the other hand, steel plates are a source of vertical stiffness and they also control rubber bulging. When a bearing has greater vertical stiffness, it will have no impact on its lateral stiffness. Moreover, a bearing generates damping, which is further augmented using oils, fine carbon blocks, resins or other fillers. HDRB systems have dominating features, including extraordinary damping and parallel actions of linear springs. We should not expect damping in an isolator to be either hysteric or viscous but something between the two [20].

4.1.8. Technical Considerations for Seismic Isolation

The need for seismic isolation of any building increases in the following situations:

1. Higher building safety requirements and after-earthquake usefulness.
2. The presence of horizontal design forces.
3. Alternative constructional form with lower ductility.
4. An unsafe building structure that is likely to be devastated in an earthquake.

A new building is constructed in earthquate-prone areas following the latest building codes, which might convince some designers that there is no need for base-isolation as legal requirements have already been met; however, in reality, exactly the opposite is the case. The designs, which follow seismic codes, have somehow been designed for more damage-prone buildings as they are constructed according to a specific design philosophy as compared to those which are base-isolated.

Traditional building codes show only a philosophy mentioning that buildings can be built as per these requirements:

1. A constructed structure must resist minor earthquakes and not be damaged.
2. It should also resist medium level earthquake with no structural damage; however, a very small amount of non-structural damage is acceptable.
3. A building should not collapse in a severe earthquake; however, it may have structural and non-structural damage.

In most countries, these rules are applicable to older buildings rehabilitated for habitation. Base-isolation is very helpful in providing a number of cutting-edge aspects to traditional structures, and it is an important step towards safer and more secure seismic engineering. For retrofitting, there is an obvious requirement to isolate the foundation because otherwise, the building will not be safe during an earthquake. When a building has suitable base-isolation, it will perform better in comparison to fixed-based buildings [69].

4.1.9. Seismic Control of Structures

Commonly, a building has to sustain shaking during an earthquake, which can vary according to the magnitude and size of earthquake waves. In such cases, these waves may result in destabilizing or collapsing a building.

The possibility of an earthquake should never be ruled out or ignored while designing a building. This is specifically true for multi-storey buildings that can pose danger to human lives. Some processes are very helpful to make this happen. Passive control is one such technique that does not require external energy to stabilize.

Base-isolation, as discussed earlier in detail, is a reliable passive system involving foundational isolation with the help of bearings. Again, there is a variety of bearings options from which to select. These bearings perform as base-isolators and they deflect and absorb destructive earthquake waves and protect buildings from harmful vibrations.

Base-isolation processes are very popular because they are easy to implement. Moreover, they can be added to any fixed-base building. According to experts, they are more useful if they are installed in taller buildings of up to 20 stories [70].

4.1.10. Ground Motion and Load Modeling

Modeling critical possibilities, for example, gravity loading and ground motion(s) are significant when analyzing precautionary measures to resist an earthquake. We have summarized some of the approaches in this context.

Many input motions/seismic movements are discussed . For dynamic analyses, experts recommend using response spectra and time histories of real seismic motion. To carry out equivalent static analyses, which are mentioned in seismic codes, design spectra are used for the estimation of horizontally applied forces.

Table 4.4. Typical Methods of analyses and relative earthquake input representations.

Method	Analysis type	Reference	Representation	Application
Dynamic	Multi-modal spectral	4.6.1.1	Spectrum	Irregular structures
	Response history	4.6.1.2	Time history	Irregular,highly-inelastic and significant structures
	Incremental dynamic	4.6.1.3	Time history	Irregular, highly inelastic and important
Static	Equivalent	4.6.2.1	Fixed	Regular and ordinary
	Conventional pushover	4.6.2.2	Fixed	Regular and important structures
	Adaptive	4.6.2.2	Spectrum	Irregular and important

Many time histories are part of today's earthquake-resistant building rules and these rules form the basis for dynamic analyses. Normally, they are 3-7 records towards every conceivable direction of possible structural responses [71]. For those structures expected to have long life, they are expected to resist asynchronous seismic motion despite temporal and spatial input differences [72].

A synchronizing/incoherent response might occur because of the frequency/time domains. Clough et al. [73] and Kavan et al. [74] presented further detail regarding the frequency-domain analyses while a number of experts presented analytical approaches to asynchronous analyses through response history [32].

Many loads can apply on any structure within its useful life. These loads can be dead loads or loads due to actions of people or movements. It is easy to model dead loads using the Gaussian distribution with the help of the coefficient of variation. Since a live load exhibits high variability, representing them largely depends on exactly what load is considered and taken. Moreover, in the case of a seismic movement, live loads are not at their peak value. In this context, a combination of loads is very appropriate. Normally, a dead load is static in nature and simply exists in the form of a structure's own mass, its accessories or partition(s), finishing or regular fixture(s). In contrast to dead loads, live loads are impermanent and depend on the usage and/or occupancy of a building. A seismic code helps to obtain the characteristic values of design loads.

Horizontal loads, such as earthquakes and strong winds, occur after some time. Seismic loading is mainly the structural mass that accelerates during an earthquake because of the movement in the earth. In general, the loads are proportional to the structural and seismic characteristics. Whenever there is a need to calculate seismic load, overall structural mass does not contribute to either total dead or live loads. It is possible that when a seismic movement occurs, a building has full operational load containing both load types. Moreover, most of the live loads are not strongly fixed to their positions, so some of them might not show any movement with the remaining structure. Here, it is helpful to convert the overall load in the form of dead and live load percentages. WEQ here is the tributary seismic weight and MEQ is the mass that corresponds with WEQ. WEQ can be mathematically described as:

$$WEQ = P_1 D_L + P_2 L_L \tag{4.1}$$

WEQ is the seismic weight, P_1 and P_2 are live and dead load percentages, respectively, D_L is the dead load and L_L is the live load. Generally, P_1 is taken as unity while P_2 varies, and mass MEQ accelerates through the seismic movement, which can be calculated by dividing WEQ (Eq. 4.1) by gravitational acceleration, g. The first step in this process is to define MEQ; then gravity and seismic loads are found or assumed.

4.1.11. Combinations of Seismic Loads

Both types of load must be added for the required structural response analyses through processes mentioned in Section 4.6. The load combination occurs according to the following equation:

$$L = \gamma_D . D_L + \gamma_L . L_L + \gamma_E . E_Q \tag{4.2}$$

In this equation, L is the total load, $\gamma_L$is the load factor for dead loads D_L, live loads L_L and E_Q for earthquakes. Experts believe that at least two load categories should be included for design and analysis. The γ_E factor value and its combination with other variables depend on limit states which are used to assess the performance of a structure.

The load factor γ_L is used in Eq. 4.2 which shows that the load values are variable and that lower load factors do not significantly vary in comparison with the characteristic value. More specifically, the factors can be 20% to 30% higher in comparison to γ_D since $L_L s$ is more uncertain relative to D_L [32].

4.1.12. Material/Frictional Non-Linear Property Isolation Bearings

4.1.12.1. Elastomeric Bearings

These are traditionally manufactured using rubber and they include low- and high-damping bearings. Low-damping bearings show shear stiffness effective for excessive shear strain (greater than 100%). Experts believe that the damping should be between 2 and 5 and of the critical level. LRBs are manufactured with the help of low-damping rubber and contain a lead core, which improves the bearing's energy dissipation by 20-30%. A higher starting stiffness helps to improve the rigidity to bear wind and minor seismic loads. Therefore, the characteristic strength will be:

$$Q = A_p \sigma_{YL} \tag{4.3}$$

Here, A_p is the lead-plug area under σ_{YL} which is the lead shear stress. K_p is the post-yielding stiffness which is generally greater than a bearing's shear stiffness that does not have a lead core.

$$K_p = \frac{A_r\, G}{\sum t}\, f \tag{4.4}$$

4.1.12.2. Rubber Isolator Function

During a seismic movement, the isolator rubber functions not unlike a spring because it has horizontal softness and vertical stiffness. More vertical stiffness is possible using thin rubber layers reinforced using steel shims. Both of these properties help isolators to move horizontally, thereby having less stiffness; however, they have significant capacity to handle axial loads with the help of more vertical stiffness. A lead core helps to provide damping through plastic deformation as an isolator makes horizontal movements when an earthquake strikes it.

Here, A_r equals the bonded rubber area, $\sum t$ the thickness of the rubber, G the rubber shear modulus, and f a larger-than-unity factor. Following the appropriate situations, f can be either less than or equal to 1.15. In addition, the initial elastic stiffness K_e remains 6.5 to 10 times the post-yielding stiffness.

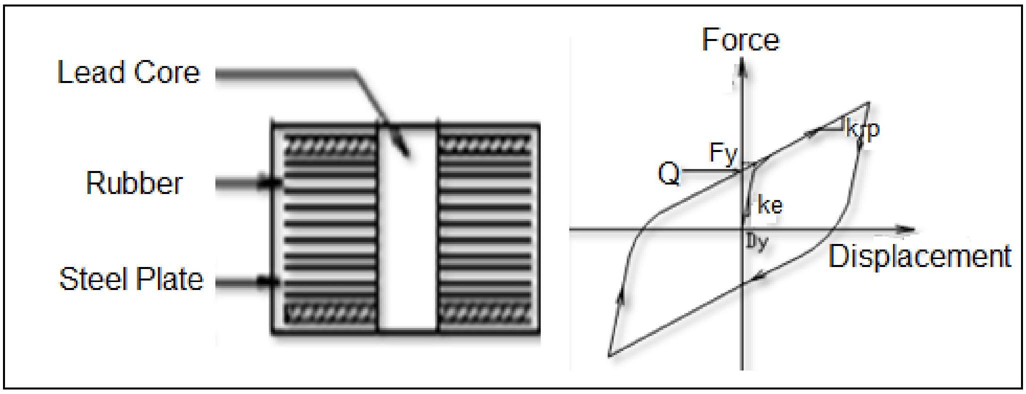


Figure 4.1. Lead rubber bearing bilinear force-displacement loop.

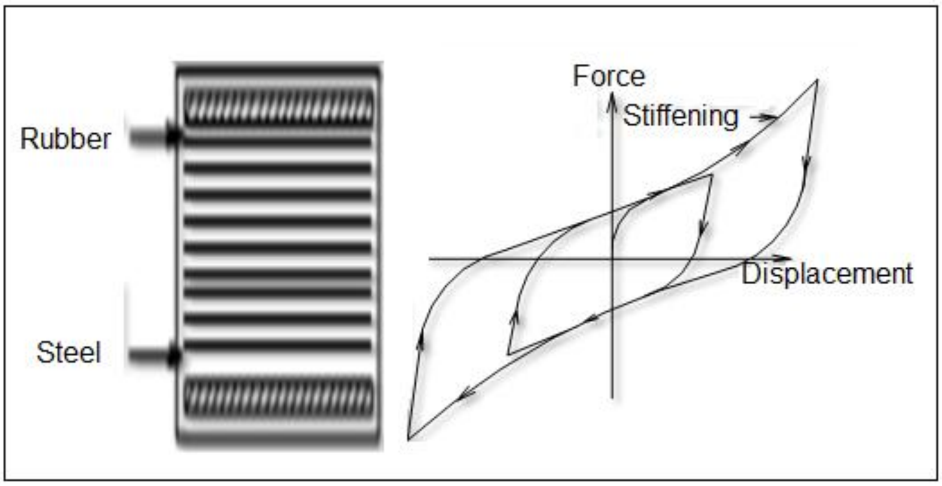


Figure 4.2. High damping bearing: force displacement loop with stiffening.

Energy dissipation and stiffness of high damping bearings are generally non-linear, which depends on shear-strain, as illustrated in Figure 4.3. Generally, high-damping bearings are manufactured using a specific compounded rubber that has 10-15% damping of critical value. This excessive damping is coupled with extra shear stiffness, which is generally less than 20%, and provides rigidity while facing a wind load and minimum seismic loads. This shear stiffness is generally lower and remains between 20% and 120% of shear strain.

When shear strain is higher, it increases shear stiffness because of strain-crystallizing within the structure of a rubber. The HDBs' damping is substantial because they join viscous and hysteretic behaviors. During the initial stages or in the first movement cycle, these bearings have more damping and stiffness in comparison to later cycles. During the third cycle, the stiffness becomes stable and brings scraggy characteristics into action. Scragging creates internal changes in a rubber. Bi-linear hysteretic models show strain values up to 200%, which shows a bearing's scragged state. This stiffening is illustrated in Figure 4.3 Afterwards is becomes possible to represent strain through complicated models. These processes show how high-damping bearings help to reduce seismic effects using bi-linear hysteretic models. The parameters of bi-linear models with the help of prototype bearing test the data. The characteristics of the shear modulus G, damping ratio ζ (which dissipates energy in motion cycles/4π at the highest kinetic energy) with scragged situations, and G is linked to after-yielding stiffness $K'p$, thus:

$$K'p = \frac{GAr}{\Sigma t} \tag{4.4}$$

These model parameters can be analyzed with the help of the mechanical characteristics of G and ζ on a specified strain level, such as parameters that correspond to the displacement of a design. Post-yielding stiffness is represented by $K'p$, which can be calculated using Equation 4.2, while characteristic strength Q is linked with the mechanical aspects of bi-linear hysteretic behavior. In this case, yield displacement Dy remains in the range 0.05 to 0.1 times the rubber thickness and D is the design displacement. The yield force Fy can be expressed as:

$$Q = \frac{\pi\xi K'pD^2}{(2-\pi\xi)D-2Dy} \quad (4.5)$$

Moreover, the ratio between post- and pre-yielding stiffness can be obtained through elastomeric bearings, which have limited vertical stiffness. This ratio has an impact on an isolated building’s vertical response. It is possible to estimate the vertical stiffness of elastomeric bearings with the following equation [75]:

$$Fy = Q + K'pDy \quad (4.6)$$

4.2. ANSYS SIMULATION STEPS

ANSYS is a popular software package that is used for different studies of physics, other sciences and fields of engineering simulation according to requirements. Researchers all over the world believe in he effectiveness of ANSYS for engineering applications.

This is a major development in terms of simulations having differint breadths and depths. It offers precision in terms of engineering measurements and it possesses a multi-phase foundation and adaptable design. ANSYS has added remarkable value to engineering design for efficient delivery, cutting-edge innovation and overcoming constraints, which helps in conducting those experiments that are otherwise impossible.

4.2.1. ANSYS Mechanical

ANSYS Mechanical is an analysis technique to conduct structural analyses for dynamic, linear, and non-linear studies. ANSYS Mechanical also provides facilities to conduct thermal analyses and to find other properties, such as electricity, acoustics, thermal-structure and thermo-electrical analyses.

Moreover, ANSYS also acts as general-purpose software that simulates interactions from different fields of physics and chemistry, including vibration, structure, heat, fluid dynamics and magnetism for engineering applications. ANSYS is software that performs simulations and tests and helps to create virtual situations prior to producing anything practically. Moreover, finding weaknesses, assessing computing life and predicting issues become possible through virtual 3D simulations. With ANSYS, it is possible to create a list of viable standard structures and analyze the options. ANSYS is well-integrated with other engineering packages such as Computer Aided Design (CAD). ANSYS is fully capable of importing CAD files and performing complex mathematical calculations using its "pre-processing" features. Using the same pre-processors, it requires meshes to generate computations. When forming loadings and concluding analyses, results may be viewed as numerical or graphical. ANSYS quickly performs advanced engineering analyses using contact algorithms, time-based loading and non-linear material modeling. ANSYS Workbench integrates simulation techniques with a parametric CAD system thereby allowing process automation. ANSYS Workbench is also an advanced form of ANSYS converging algorithms.

ANSYS Workbench is highly compatible with the PC, and it is more than merely an interface. ANSYS may be a general finite part code usually used when a deformable half is not undergoing large rigid-body motions. However, it results in a high spatial resolution for stress or strain given the required square measure. A typical field of application is that the proof of the strength of elements. LS-DYNA is additionally a finite-element code; however, with a specific stress on the specific problem solver, it is numerically efficient for the simulation of large short-time scenarios. A typical application is the crash simulation.

4.2.2. Steps to Resolving Problems Using ANSYS

For analytical problem-solving, a researcher should first define where the solution actually lies and know the following:

1. The physical model
2. The boundary situation
3. Any physical properties

The next step is to solve a problem and present its outcomes. Numerical strategies show that mesh-generation is a very important step that changes a complicated model into divided elements to make it solvable. The following points shed light on important terminologies:

1- Building Geometry: It is essential to make a 2D or 3D object representation for modeling and testing with the help of defining coordinates using ANSYS.
2- Defining the Material: It is necessary to define the properties of a material using the material library. This helps in modeling different projects. Material definition involves thermal and mechanical properties.
3- Generating a Mesh: This step is essential in creating an ANSYS project. The modeled system is dampened into finite items.
4- Applying a Load: When a system has a shape in terms of the design, burdening with loads is the final task.
5- Acquiring a resolution: This is a necessary step because ANSYS needs to know in what situation an issue will be resolved.
6- Presenting Results: When ANSYS finds a solution, the results should be presented in the desired form, such as a graph, chart, contour plot or table, as shown in Figure 4.3.

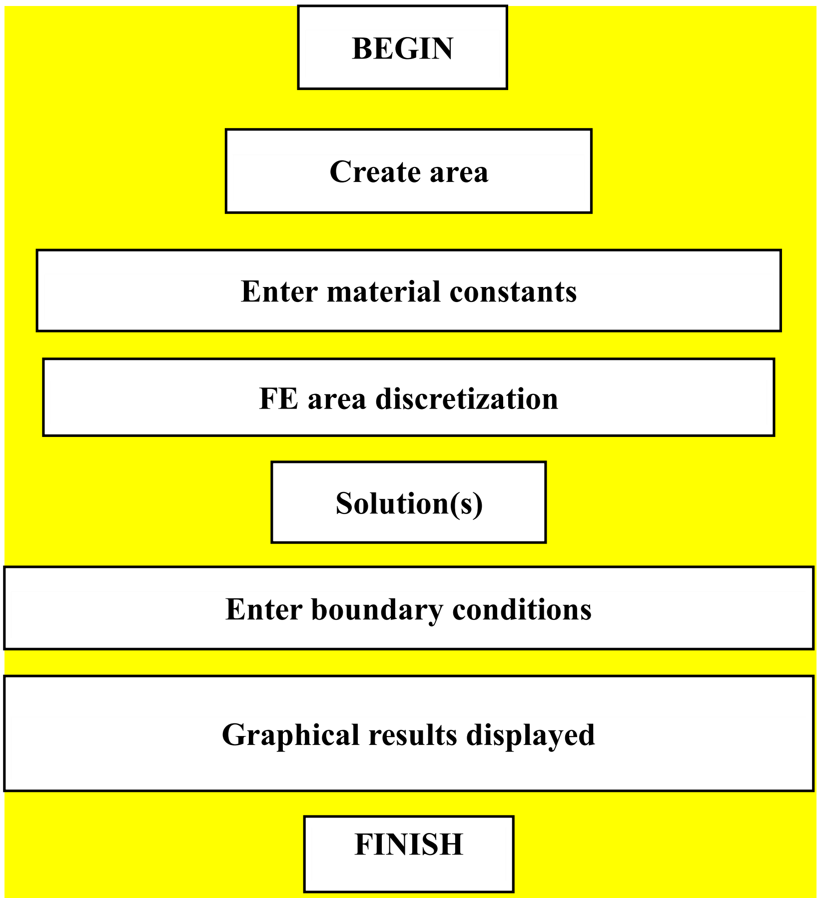


Figure 4.3. ANSYS structural analysis flowchart.

4.2.3. Element Types Used in APDL ANSYS

4.2.3.1. COMBIN14 Spring-Dampers

COMBIN14 possesses longitudinal capabilities for use in single-dimension, 2D and 3D applications. It provides a longitudinal option pertaining to uniaxial tension-compression elements with up to three degrees of freedom on every node in the x, y, and z directions. It does not consider any bending or torsion.

A spring-damper possesses no mass, which is possible to add with the help of a suitable mass component (MASS21). A spring/damping is eliminable from a building. For details, observe COMBIN14 in Mechanical APDL. Any spring/damper plays a role towards stiffness matrix elements (MATRIX27). Another example of a spring-damper is COMBIN40.

4.2.3.1. COMBIN14 Input Data

COMBIN14 Geometry: An element is definable through two nodes including spring constant k and damping coefficients c_v 1 and c_v 2. This damping does not apply to static or undammed modal analysis. A longitudinal spring requires force/length units. Torsional spring constants and damping coefficients use units of force×length/radian and force×length×time/radian. In cases of 2D axi-symmetrical analyses, the values must be at 360°. Damping portions only contribute to the damping coefficients. We can calculate the damping force F and torque T from the formulae given below:

$$Fx=\frac{c_x d_{ux}}{dt} \text{ or } T_\Theta=-\frac{c_v\Theta}{dt} \qquad (4.7)$$

Here, c_v is the damping coefficient, which can be calculated through:

$$c_v = (c_v)1 + (c_v)\tfrac{1}{2}v \qquad (4.8)$$

Here, v is the velocity that was found during the last step. Another damping coefficient $(c_v)2$ produces non-linear damping effects. When the input is $(c_v)2$, KEYOPT1 should be 1.

KEYOPT 2 = 1 to 6, which is true for single-dimensional elements. These elements operate through nodal coordination systems. Here, KEYOPT 2, 7 and 8 allow the use of an element to conduct a thermal/pressure analyses.

The spring pre-load can be mentioned through one out of the two methods: either through basic force-free length (or ILENGTH) or through the initial force or IFORCE inputs. Only one input option can be utilized to define a pre-load. When the length in the beginning is different as compared to the input length, which is obtained through the node coordinates, pre-load can be presumed. When there is an initial force, which we know, negative values show spring compression while positive values show tension.

4.2.4. MASS21 Element Description

This is considered a point-element with up to 6 degrees of freedom in the $x, y,$ and z directional translations and in the x, y, and z directional rotations. Each coordinate is assigned with different masses and rotary inertias. MATRIX27 is also an element with full-mass matrix capabilities.

4.2.4.1. MASS21 Input Data

This is explained using only one node, its mass components (Force × Time2/Length) towards the coordinate direction, and rotary inertias (Force × Length × Time2). These elemental coordinates can be parallel to the Cartesian coordinate system in the beginning or to the KEYOPT 2 nodal coordinate system. These systems rotate through coordinate rotations. Many options exclude rotary inertias, which reduces the elements to 2D (KEYOPT 3). When the elements need only a single mass input, it acts in many coordinate directions. It is illustrated in KEYOPT 1 which defines mass in the form of volume × density, and makes it easy to plot the mass with the help of ESHAPE and temperature-dependent densities.

4.2.4.2. MASS21 Output Data

Nodal displacements are part of a whole displacement solution. Every element has to encounter some element reaction forces or energies.

4.2.5. BEAM188 Element Description

BEAM188 is appropriate to analyze slim to thick beams. These elements depend on Timoshenko's beam theory that takes into account shear-deformation impact. These elements provide opportunities to conduct both restrained and unrestrained warping in the cross section. These elements show a linear trend and quadratic/cubic double-node beams in 3D. BEAM188 possesses 6 or 7 degrees of freedom on every node, which includes translation in the x, y, and z directions as well as rotation in these directions. A degree of freedom is possible but optional. It suits linear, high-rotation, and large-strain, non-linear applications. It includes stress-stiffness with large deflections. The achieved stress-stiffness enables elements to analyze horizontal, flexural, and torsional balance issues. Creep, elasticity and plasticity and further non-linear material models receive support. The cross-sectional association can be established with this type of element with more than a one material. Additional mass, loading, hydro-dynamic additional mass and buoyant loading are present in this case.

4.2.6. SOLID185 Element Description

SOLID185 helps to create solid structural 3D models. It is defined by 8 nodes and 3 degrees of freedom on every node. Its translations take place in the $x, y,$ and z directions. The elements are plastic, hyper-elastic and stress-stiffened with large deflections and maximum strain-handling. It possesses capabilities of simulating the deformation of most non-compressible elasto-plastics, and completely non-compressible hyper-plastics [76].

4.2.7. Generating a Mesh

Generating mesh is a process that includes the following three processes:

1. Adjusting the attributes of the elements
2. Mesh control
3. Generating the mesh while selecting free meshing from the mesh toolbox (sweep) start for meshing. Now, ANSYS comprehends the half makeup and the modelled system needs finite reduction.

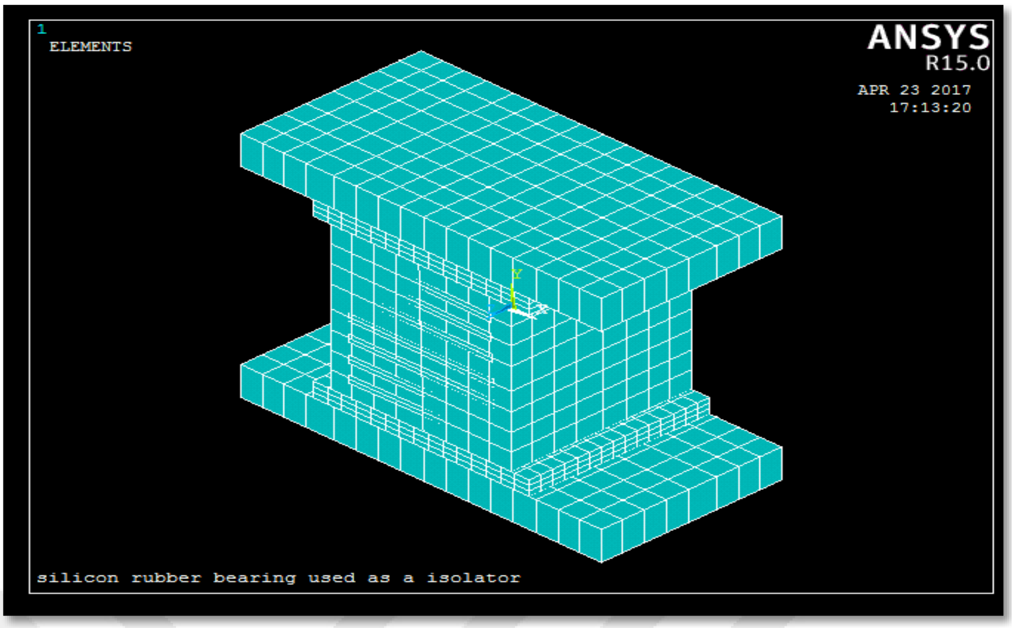


Figure 4.4. Image1-Schmatic diagram of base isolation syetem rubber and steel 3D.

4.2.7.1. Building the Geometry

First, a 2D or 3D object should be modelled thus:

1. Rubber dimensions, length = 1.0 m, h = 1.0 m, width = 1.0 m.
2. Steel dimensions, length = 0.8 m, width = 0.8 m, thickness = 0.05 m.
3. Small upper plate dimensions, length = 1.20 m, width = 1.0 m, thickness = 0.1m.
4. Large upper plate dimensions, length = 2.0 m, width = 1.0 m, thickness = 0.2 m.
5. Small bottom plate dimensions, length = 1.20 m, width = 1.0 m, thickness = 0.1m.
6. Large bottom plate dimension, length = 2.0 m, width = 1.0 m, thickness = 0.2 m.

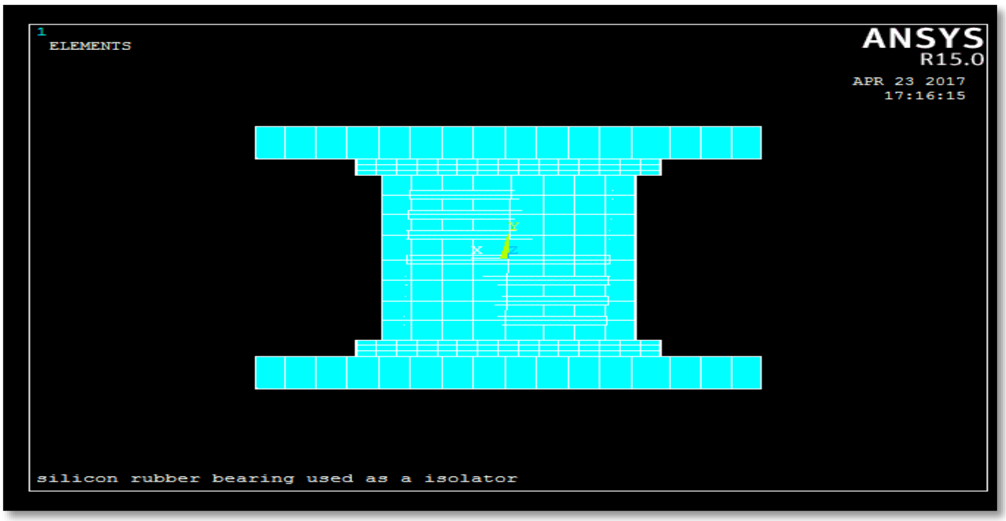


Figure 4.5. Image 2 schmatic diagram of base isolation system (rubber and steel).

4.2.7.2. Defining Material Properties

1. In the pre-processor step use material types as type one (solid) with options as beam 188, 3-D Coupled for steel structure as plate, and for rubber structure combine 14, as damper 14 use spring damper.
2. For Type 2, we use Solid185 for full integration and to define the whole material. For the degree of freedom, we use U_x, U_y, U_z ,ROT_x ,ROT_y , ROT_z and coupled-Physics Capabilities use Hyper Elastic Coupling.
3. For the material properties, we select SI units, and for the model of the material, we define Model 3 using the density of the material applied for the steel and rubber (steel density = 7850 kg/m^3 and rubber density = 1150 kg/m^3). Currently with the above information, we describe the required modelled materials including their mechanical properties.

4.2.8. Applying Load

For the solution, we define the load as the velocity, acceleration and displacement on both areas, top and bottom. We also apply U-notch the area as up with displacement value on the top and bottom (+0.001, −0.001). We apply a voltage to the area on the top and bottom (+5, −5 volts), as shown in Figure 4.4. After the structure design is completed, a new task loads a system using restraints such as physical loading or boundary conditions.

4.2.9. Dynamic Equations in ANSYS

$$M_1\ddot{x}_1 + C_1(\dot{x}_1 - \dot{\delta}(t)) + C_2(\dot{x}_1 - \dot{x}_2) + K_1(x_1 - \delta(t)) + K_2(x_1 - x_2) = 0$$

$$M_2\ddot{x}_2 + C_2(\dot{x}_2 - \dot{x}_1) + C_3(\dot{x}_2 - \dot{x}_3) + K_2(x_2 - x_1) + K_3(x_2 - x_3) = 0 \qquad (4.9)$$

$$M_3\ddot{x}_3 + C_3(\dot{x}_3 - \dot{x}_2) + C_4(\dot{x}_3 - \dot{x}_2) + K_3(x_3 - x_2) + K_4(x_3 - x_4) = 0 \qquad (4.10)$$

And so on…

$$M_{39}\ddot{x}_{39} + C_{39}(\dot{x}_{39} - \dot{x}_{38}) + C_{40}(\dot{x}_{39} - \dot{x}_{40}) + K_{39}(x_{39} - x_{38}) + K_{40}(x_{39} - x_{40}) = 0 \qquad (4.11)$$

$$M_{40}\ddot{x}_{40} + C_{40}(\dot{x}_{40} - \dot{x}_{39}) + K_{40}(x_{40} - x_{39}) = 0 \qquad (4.12)$$

4.2.9.1. Mass Matrix as in Matrix (4.13)

$$\mathrm{M} = \begin{bmatrix} M_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & M_2 & 0 & & & & & & \\ 0 & 0 & M_3 & 0 & 0 & & & & \\ 0 & & & & & & & & \\ . & & 0 & 0 & & & & & \\ . & & & & & & & & \\ 0 & & & & & 0 & 0 & M_{39} & 0 \\ 0 & & & & & 0 & 0 & 0 & M_{40} \end{bmatrix} \qquad (4.13)$$

4.2.9.2. Stiffness Matrix as in Matrix (4.14)

$$K = \begin{bmatrix} (K_1+K_2) & -K_2 & 0 & 0 & 0 & 0 & 0 & 0 & . & . & 0 & 0 \\ -K_2 & (K_2+K_3) & -K_3 & & & & & & & & & \\ 0 & -K_3 & (K_3+K_4) & -K_4 & & & & & & & & \\ 0 & 0 & -K_4 & & & & & & & & & \\ . & & & & & & & & & & & \\ . & & & & & & & & & & & \\ 0 & & & & & 0 & 0 & (K_{39}+K_{38}) & -K_{39} & & & \\ 0 & & & & & 0 & 0 & -K_{39} & (K_{40}) & & & \end{bmatrix} \quad (4.14)$$

4.2.9.3. Damping Matrix as in Matrix (4.15)

$$C = \begin{bmatrix} (C_1+C_2) & -C_2 & 0 & 0 & 0 & 0 & 0 & 0 & . & . & 0 & 0 \\ -C_2 & (C_2+K_3) & -C_3 & & & & & & & & & \\ 0 & -C_3 & (C_3+C_4) & -C_4 & & & & & & & & \\ 0 & 0 & -C_4 & & & & & & & & & \\ . & & & & & & & & & & & \\ . & & & & & & & & & & & \\ 0 & & & & & 0 & 0 & (C_{39}+C_{38}) & -C_{39} & & & \\ 0 & & & & & 0 & 0 & -C_{39} & (C_{40}) & & & \end{bmatrix} \quad (4.15)$$

4.2.9.4. Forcing Function

$$[77] = \begin{Bmatrix} C_1\dot{\delta}(t)+K_1\delta(t) \\ 0 \\ 0 \\ . \\ . \\ 0 \end{Bmatrix} \quad (4.16)$$

4.2.9.5. Displacement Vector

$$[78] = \begin{Bmatrix} X_1 \\ X_2 \\ . \\ . \\ . \\ X_{40} \end{Bmatrix} \tag{4.17}$$

4.2.9.6. Differential Equations of A System in Matrix Format

$$[M]\{\ddot{X}\}+[C]\{\dot{X}\}+[K]\{X\}=\{F\} \tag{4.18}$$

4.2.10. Structural Design for Multi-Level Approaches

The one-limit-level procedure was, for a long time, the basis of code provisions. Recently, the modern codes (EC8 and UBC 97) introduced checks for two limit levels. Future codes are expected to consider three limit levels and two-level design. This seismic design philosophy is connected to the traditional design methodology for other loading types for which two levels are considered. However, for seismic loadings, there are some features in design criteria that must be underlined. Structural demands are presented. For the two-level design, checking the two demands, rigidity and strength, must be considered as a basic verification. The other checks, such as strength for limitation of damage, or ductility for ultimate limit state, are optional three-level designs. This methodology differs from the previous approach not only for the number of levels but also for a clearer definition of the performance levels. The design criteria are presented as follows:

1. For serviceability limit level under frequent low earthquakes, the strategy calls for the complete elastic response of the structure. Lateral deformations are limited by inter-storey drift limits given for non-structural elements. In order to guarantee their integrity, the interaction between structural and non-structural elements must be considered. The basic verification of structural rigidity and

strength verification conditions for elastic behavior is only optional;

2. For damageability level under occasional moderate earthquakes, an elasto-plastic analysis must be performed. The produced damage can be repaired without great economical or technical difficulty. The basic verification refers to structural member strengths, with checking of rigidity and ductility being optional. The non-structural elements are only partially damaged, so an analysis must consider only the structure, without any interaction with non-structural elements;
3. For the ultimate level under rare severe earthquakes, a kinematic analysis, which considers the behavior of a possible formation of plastic collapse mechanisms, must be performed. The basic verification refers to the ductility, with strength verification being only optional. The design strategy refers to the control of the formation of a pre-selected plastic collapse mechanism and the rotation capacities of plastic hinges. Non-structural elements are completely damaged (Earthquake Engineering for Structural Design, Federico) [79].

4.2.11. Isolation System Displacement

This is determined for the design earthquake with the help of standard equations.

$$D_D = \left\{\frac{g}{4\pi 2}\right\}\frac{S_{D1}\ T_D}{B_D} \quad (5.1)$$

$$T_{D=2\pi}\sqrt{\frac{W}{k_{Dmin\ g}}} \quad (5.2)$$

$$B_{D=\frac{1}{2\pi}}\left\{\frac{\sum E_D}{K_{Dmax\ D_D^2}}\right\} \quad (5.3)$$

Here, damping factor B_D relies on effective damping B_D with the help of a standard.

Table 4.5. Summary of least design criteria for dynamic analyses.

Design Parameter	Response Spectrum Analysis	Time History Analysis
Total design displacement, D_{TD}	90% D_{TD}	90% D_{TD}
Total maximum displacement, D_{TM}	80% D_{TM}	80% D_{TM}
Design force on isolation system, V_b	90% V_b	90% V_b
Design force on irregular superstructure, V_S	100% V_S	80% V_S
Design force on regular superstructure, V_S	80% V_S	60% V_S

The equation explains the top displacement with a single degree of freedom (SDOF) with T_D period and damping B_D to produce an earthquake-resistant design under the seismic coefficient s_{D1} that corresponds to 5% of spectral responses with a 1-second period. B_D changes the 5% damped response to the isolation system's damping levels. When B_D remains at 1.0, the damping B_D is 5% of the critical levels. Figure 5.2 shows the foundational concepts behind Standard Equation 5.1 having an amplitude equation for effective period T_D as well as for effective damping B_D.

These equations show the highest displacement (DM) as well as the design displacement D_D, which show differences because of corresponding earthquake levels. The highest possible displacement (DM) is linked with MCER seismic motion (SM1) while design displacement is according to designing the seismic motion (shown by s_{D1}). Normally, the damping factor and the effective period (BM and TM) help to calculate the highest displacement, which varies from the previously calculated design displacements (T_D and B_D) when there are effective period shifts while the damping changes and increases ground shaking levels. Effective period T_D calculations rely on an isolation system's least stiffness kDmin, which is achieved through the prototype testing of isolator units. In the same manner, calculating effective damping depends on the least loop area (ED), which is possible through prototype testing. Using minimum stiffness/damping generates major estimates pertaining to the effective period and peak displacement in the isolation systems. Our design displacement D_D and highest displacement DM show the highest earthquake displacement based on a building's mass center having no extra displacement, which occurs in further locations as a consequence of actual/accidental mass-eccentricities. The equations that determine the total displacement and include the impact of mass-eccentricity increase displacement on the mass center. They are based on the dimensions of a plan as well as the underlying assumptions that the isolation stiffness and building mass show in a plan with a similar distribution. Increasing displacements occur on the corner of 5% mass-eccentricity that is around 15% when a plan shows a squarish building and up to 30% for long buildings. Figure 4.6 shows the design displacement D_D, maximum displacement DM on the mass center of a structure and the maximum total displacement DTM on the isolated corners of a building [80].

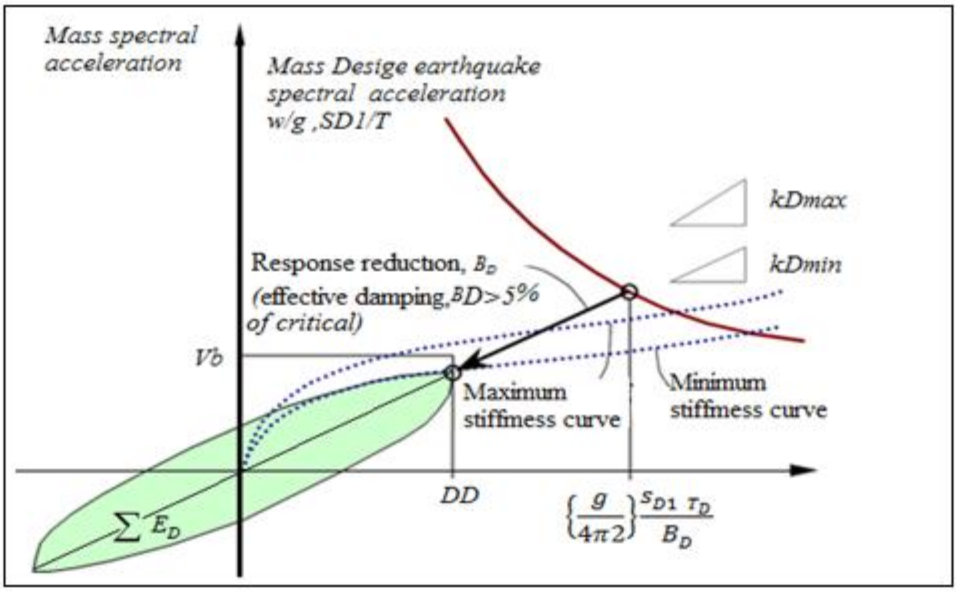


Figure 4.6. Isolation system capacity and earthquake demand.

PART 5

FINDINGS AND DISCUSSION

5.1. INTRODUCTION

Seismic isolation is a technique that has been used around the world to protect building structures, non-structural components and content from the damaging effects of earthquakes. One of the most common effects associated with an earthquake is shaking. Depending on the size and magnitude of the seismic waves, this shaking can result in varying levels of destruction. In the case of buildings, such waves can produce instability or, in more extreme cases, cause structures to collapse. Therefore, presented in this study is a theoretical background used in ANSYS for time history analysis due to seismic excitation. The effect of the types of base excitation on the responses is investigated by comparing the response histories between various excitations. In addition to the base excitations, acceleration time histories are applied to the entire model with a fixed base, which is a traditional case used in the transient analysis of seismic excitation.

The ground motion is assumed to occur in one horizontal direction so that the problem can be simplified as a two-dimensional problem without consideration of torsional effects. The superstructure is modeled as a linear multi-degree of freedom system where the mass is concentrated at each split-level and the stiffness is provided by the walls in the corresponding direction. The mass of each degree is that of the corresponding floor together with half of the wall mass of the neighboring layers. All the results of these analyses are compared with each other and the analysis characteristics are addressed for the responses, such as displacement, velocity, acceleration and response spectrum.

In order to prove the capability of the proposed hybrid isolation systems, the structural dynamic responses observed after retrofitting this system are obtained. A 40-storey building structure is subject to an earthquake load and the mass of each floor is 980000 kg. In addition, the stiffness is supposed to be linearly distributed with 1.93 GN/m and 963 MN/m for the first and fourth floors, respectively.

The building is fixed at its base. Then, the earthquake load is exerted on the structure at an acceleration of $a = 5$ g for 5 seconds; here, g is acceleration due to gravity.

$k_b = 0.001\, k_1 = 1.93 \times 10^6 \frac{N}{m}$ and $b = 0.15$.

Since the last storey undergoes the most severe dynamic loads, it was considered as the critical place to be studied. Figure 5.2 describes the displacement of the 40 storeys, wherein the maximum displacement was 1.43955 mm at the fortieth floor and the minimum displacement was 0.15995 mm. from Figure 5.3 show the displacement vs. the number of storeys and illustrates the maximum displacement in the building floors. We find that on each floor, the amplitudes of the displacement, velocity and acceleration responses of the structure with base isolation are much lower than those of the structure with displacement of a fixed base at 1.5 mm. The maximum acceleration displacement and velocity response values are shown in Figures 5.4 to 5.8. The acceleration response of the structure is significantly mitigated with base isolation and the displacement responses of the first floor and the roof of the structure are excited.

5.2. SIMULATION RESULTS OF THE EARTHQUAKE MODEL

After accomplishment of the simulation in ANSYS, the results are obtained in the form of displacement, velocity and acceleration. The results obtained from ANSYS are described as follows**.**

5.2.1 Displacement Results

Due to the mechanical properties of rubber bearings, tension forces in a rubber bearing (a result of overturning moment) and vertical seismic force must be suppressed in the design of a seismic isolation system. Since the building weight is concentrated into the large square LRBs, which are laid out along the perimeter line of the upper-level floors, the uplift force caused by the overturning moment is theoretically minimized. The large square composite materials are always under compression stress, even when considering the coupling effect of overturning caused by horizontal earthquake forces and uplift effects caused by vertical earthquake forces.

The displacement is the difference between the initial position of a reference point and any later position. The amount that any point is affected by an earthquake has moved from where it was before the earthquake.

The aim of the direct displacement-based design procedure is to develop an equivalent representation of the model structure. This is achieved by assigning strength proportions and subsequently using the moment profile in the walls to set a design displaced shape before any analysis has taken place. Knowledge of the displacement profile and recommendations for the combination of frame and wall damping components enable representation of the structure as an equivalent single degree of freedom system. Then the required effective period and the stiffness are determined using the substitute structure approach. The design base shear is obtained through multiplication of the necessary effective stiffness by the design displacement. The strength of individual structural elements is set taking care to ensure that initial strength assignments are maintained. Figure 5.1 shows the displacement distribution in the *x*-direction of the isolation system with the maximum displacement being 0.063128 mm.

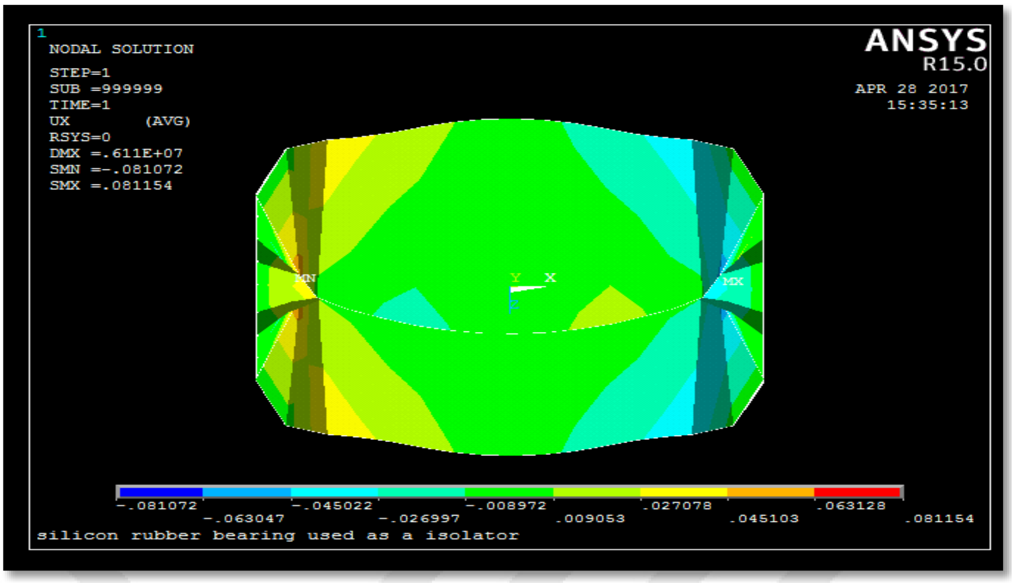


Figure 5.1. Displacement distribution in the *x*-direction of the isolation system.

Figure 5.2. describes the displacement of the 40th storey, wherrein the maximum displacement was 1.43955 mm at the fortieth storey and the minimum displacement was 0.15995 mm. Figure 5.3 shows the displacement vs. the number of storeys and illustrates the maximum displacement in the building floors.

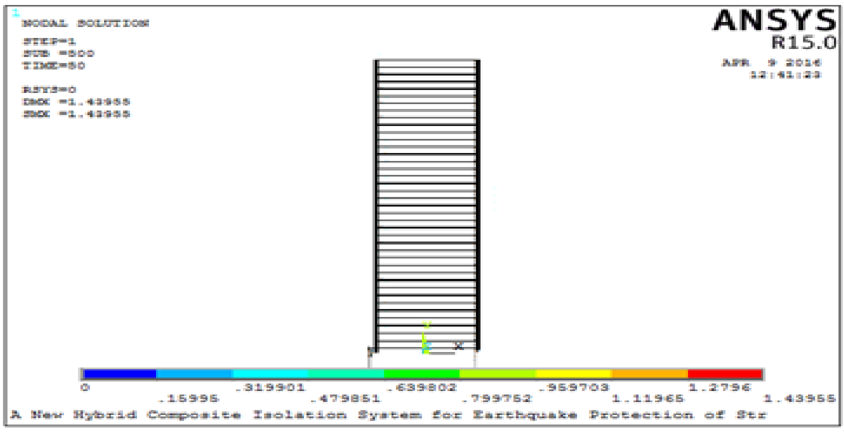


Figure 5.2. Displacement of 40 storeys in the *x*-direction.

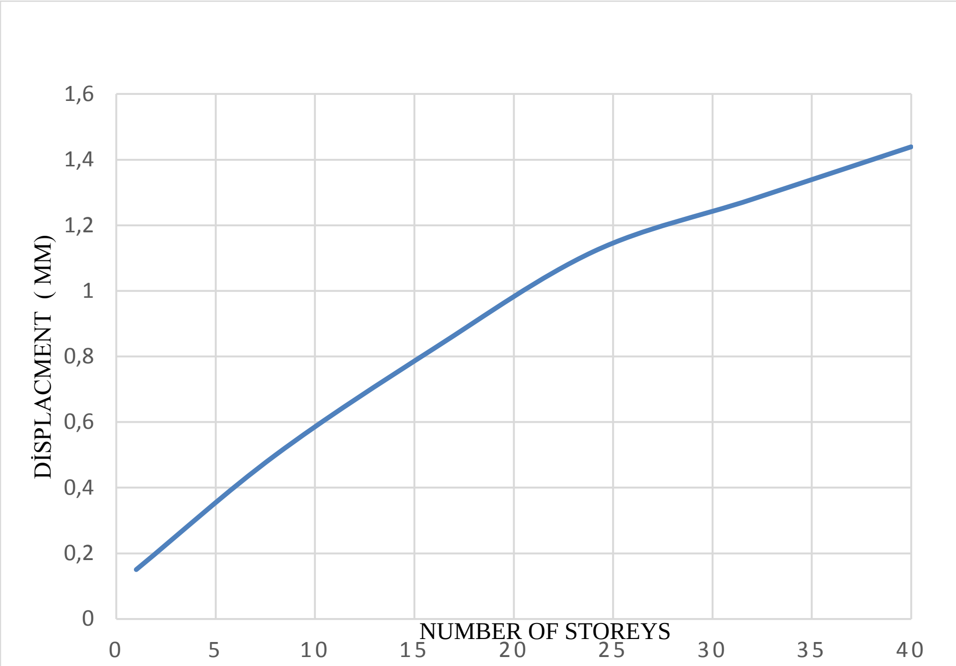


Figure 5.3. Displacement of the building vs. the number of storeys.

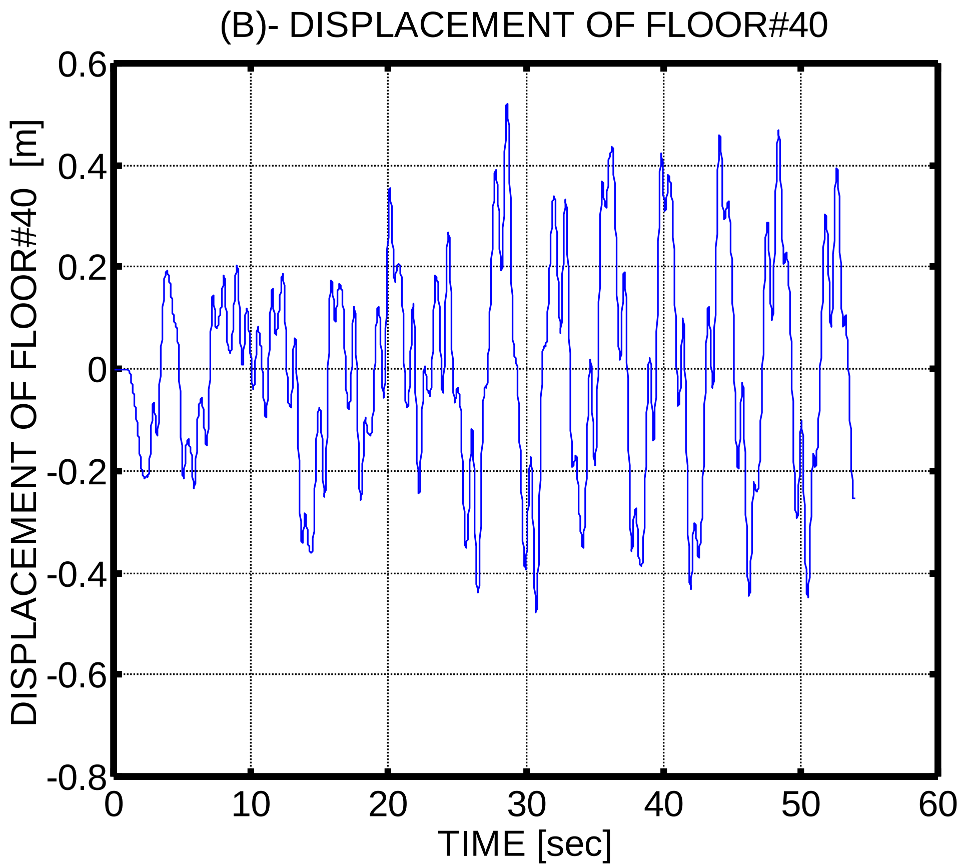


Figure 5.4. Displacement-time response of the Base and Floor #40.

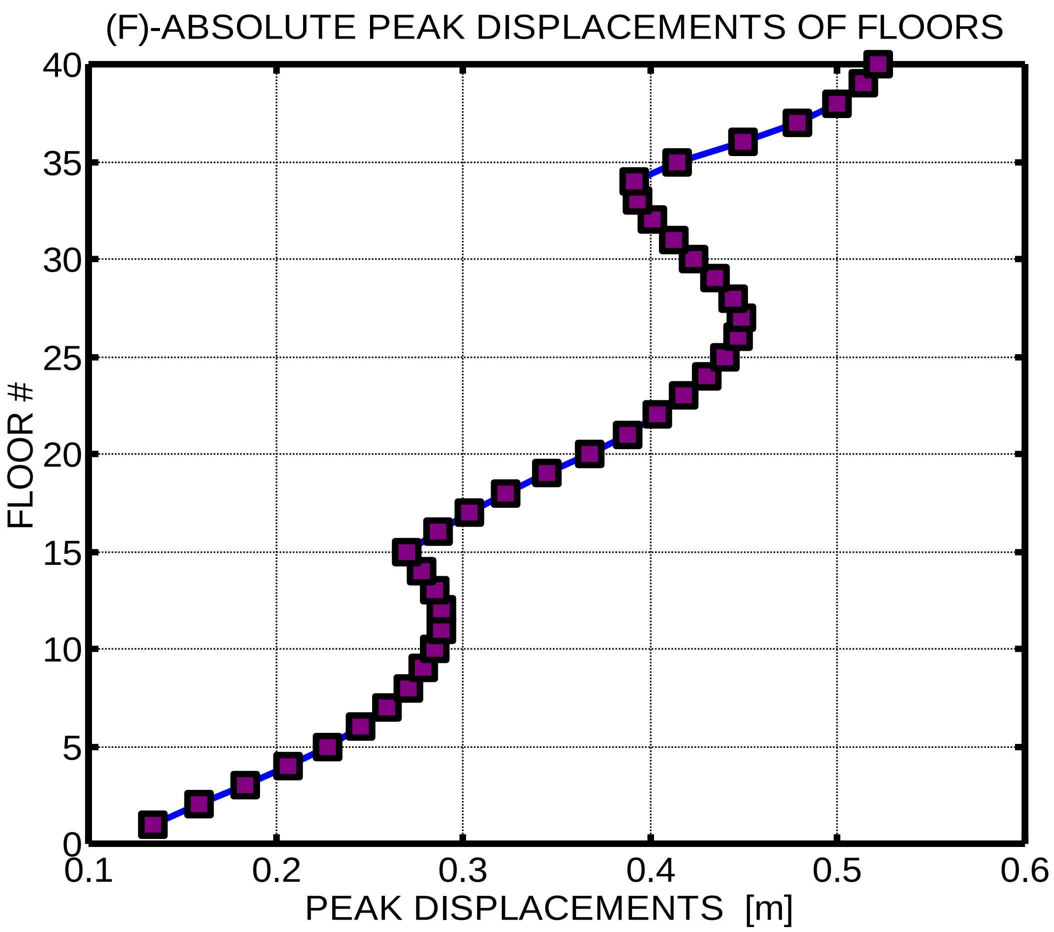


Figure 5.5. Absolute peak displacements of the floors.

5.2.2. Acceleration

In general, seismic isolation limits the effects of an earthquake attack since a flexible base largely decouples the structure from the horizontal motion of the ground. The structural response accelerations are usually lower than the ground acceleration. From Figure 5.6, the base is isolated and the segmental structures with elastic-plastic isolation systems at the base floor have lower acceleration responses compared with those associated with the ground motions.

The total acceleration (ground acceleration plus relative structural acceleration) at the base floor is greatly reduced. When comparing the total acceleration responses, the segmented buildings show smaller total accelerations at the top floor than those observed in the base isolated buildings.

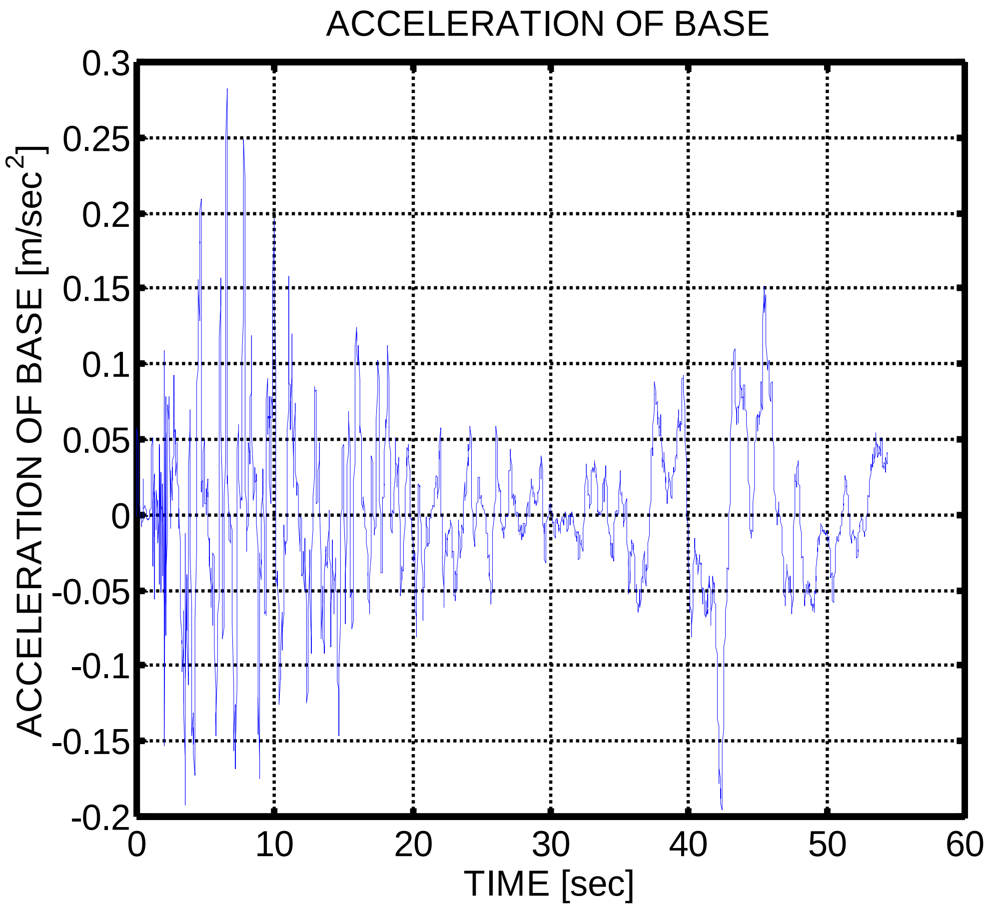


Figure 5.6. Acceleration of base vs. time.

The response results in the *x* direction for several input earthquake motions can be observed in Figure 5.7. The input earthquake motions were artificial earthquake waves created based on the maximum provided in this building, as the maximum design earthquake had assumed in building.

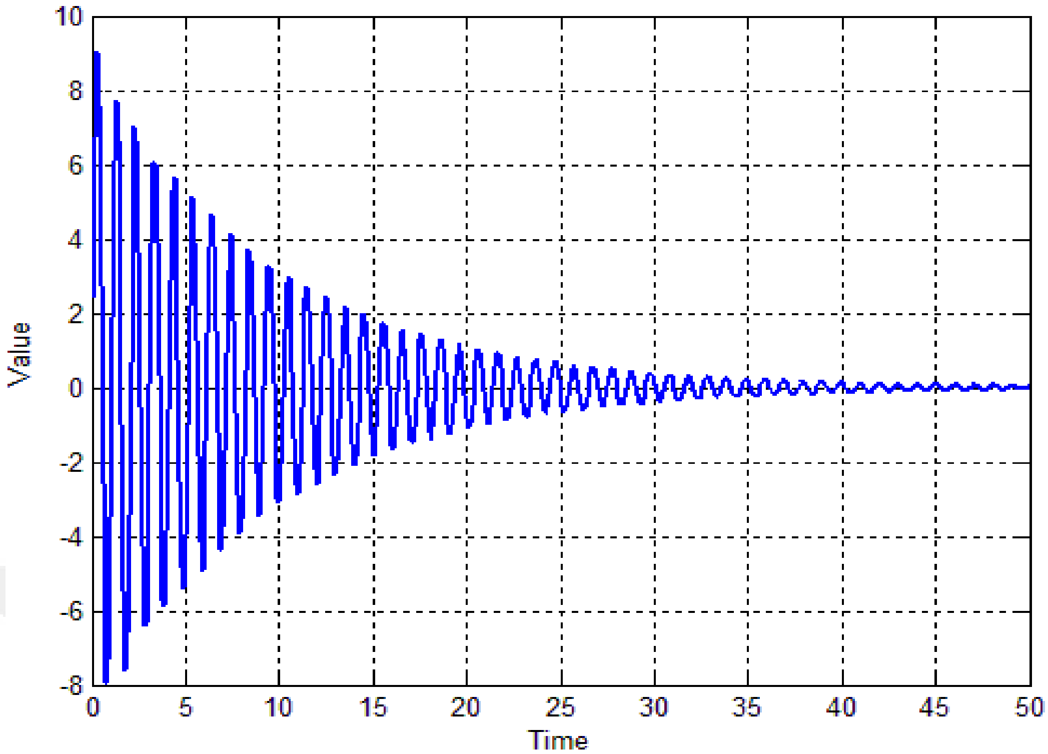


Figure 5.7. Acceleration of 40 storeys in the *x*-direction.

Response spectra are shown in Figure 5.8. According to the time history and response analysis, the maximum acceleration was less than 0.5 m/s^2. For the base isolated structure, absolute acceleration is a response quantity of interest because it is directly proportional to the forces exerted in the superstructure due to earthquake ground motion. The top floor absolute accelerations for the fixed base building and the base isolated building are plotted against time to study the effectiveness of the base isolation technique.

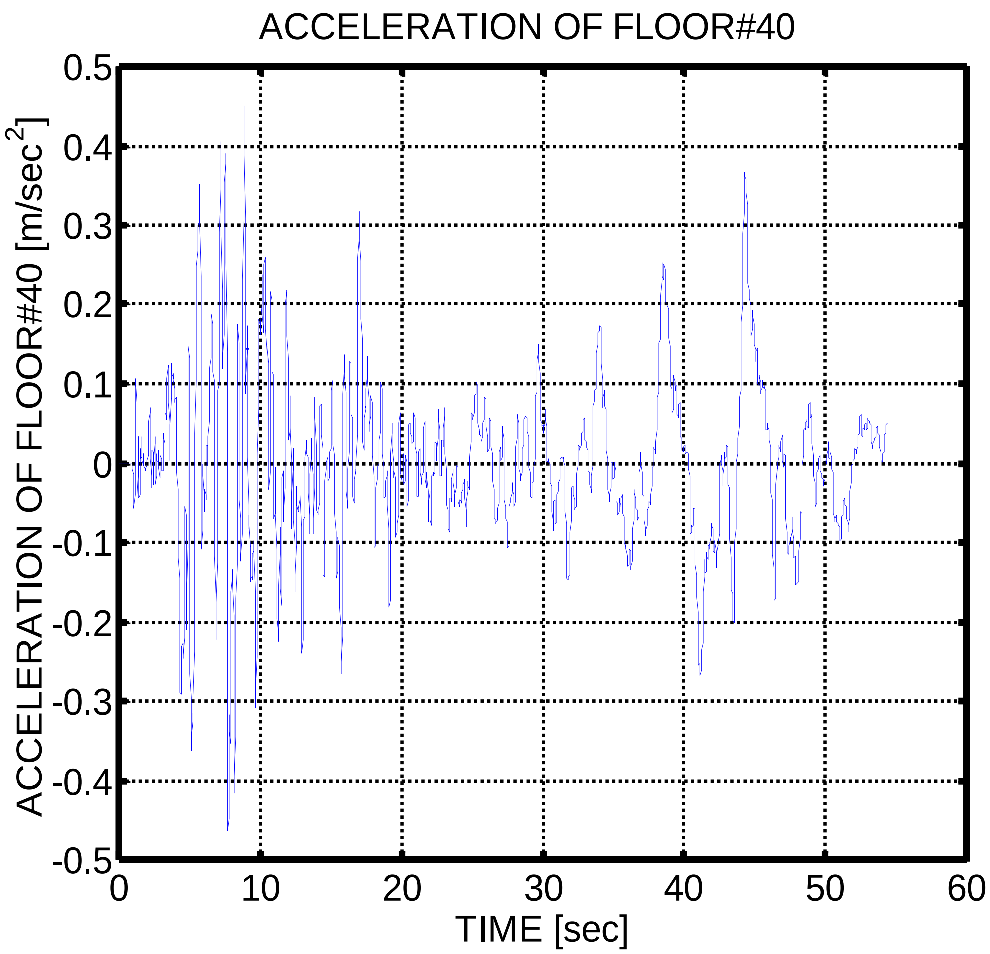


Figure 5.8. Acceleration-time response of the base and Floor #40.

Figure 5.9 shows the absolute peak accelerations of the floors.

The acceleration in both cases occurred at the top floor and was reduced as a result of the base isolation.

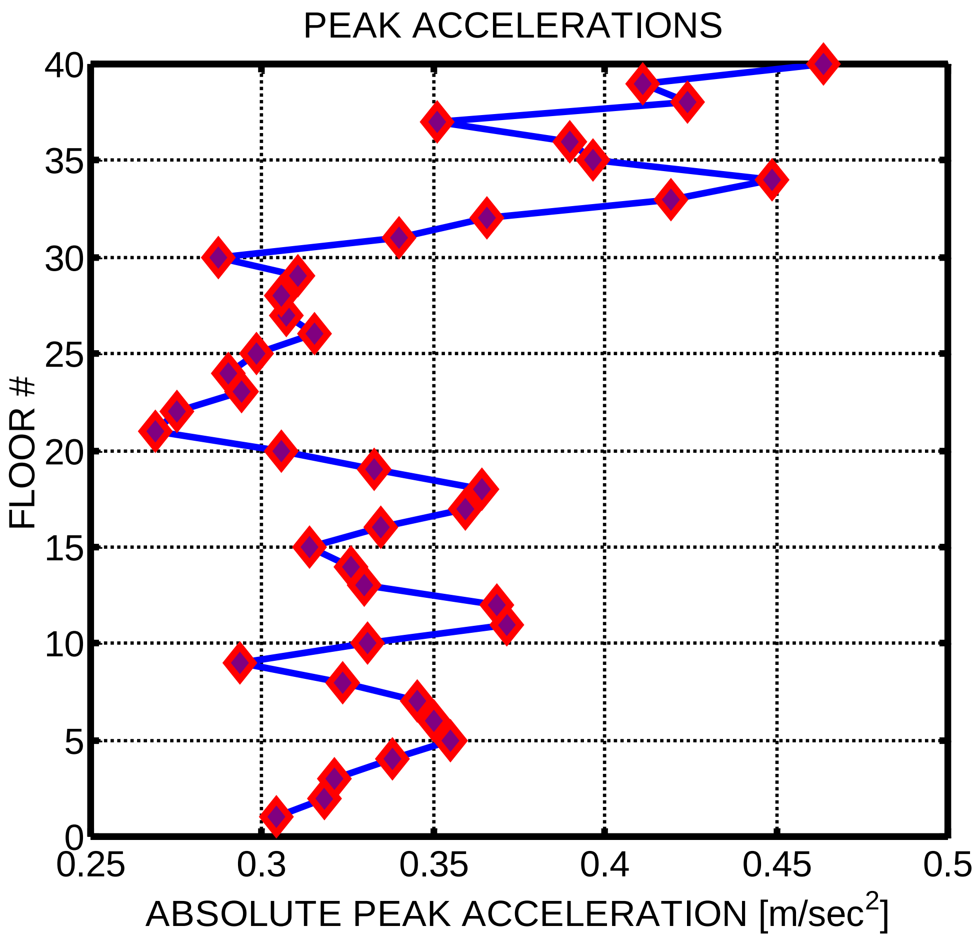


Figure 5.9. Absolute peak accelerations of the floors.

The maximum acceleration at the last storey is shown in Figure 5.10. Because the maximum displacement is at the same floor, it means that the maximum vibration occurs in this floor.

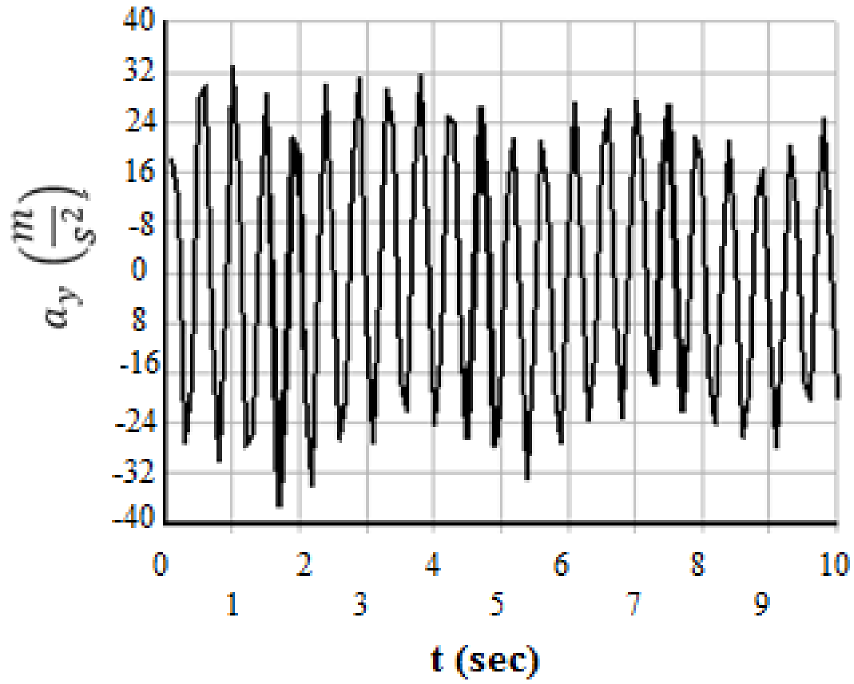


Figure 5.10. Acceleration of the last storey vs. time.

PART 6

CONCLUSIONS

A base isolation technique is one of the most commonly implemented seismic protection systems in earthquake prone areas. The term “base” refers to the foundation of a structure and “isolation” refers to the reduced interaction between the ground and the structure resting over it. It is a simple design approach to reduce earthquake damage potential. It is an implementation of a flexible or sliding interface between a structure and its foundation for the purpose of decoupling the horizontal motions of a structure, thereby reducing earthquake damage to the structure and its contents.

In this work, a new alternative base isolation system composed of common rubber and steel bearing has been invented for structural seismic mitigation.

1. The combined isolation system possesses suitable initial and post yielding horizontal stiffness. The initial stiffness is provided by the stiffness of the rubber bearing and sliding rubber bearing. The post yielding stiffness is provided by the stiffness of the rubber bearing and the friction of the sliding bearing.
2. The displacements in the upper parts of the isolated base show greater differences when compared with identical buildings with a rigid base.
3. In cases of strong intensity earthquakes, a sliding rubber bearing in a CIS would slide followed by lateral stiffness of the isolation layer decreasing. Flexible isolation then reduces the earthquake action on the structure.
4. Combined isolation system has an excellent capacity of energy dissipation due to frictional sliding.
5. Durng a high intensity earthquake, structural responses of inter-story drifts and shear forces can be reduced by 60 to 70 percent without large displacements and residual deformation of the isolator.
6. The flexibility at the base of a building increases with the use of steel and rubber

bearing isolators.

7. The use of base isolation decreases base shearing and increases displacement and the time period, proving its efficiency over fixed conditions and providing better seismic protection during earthquakes.
8. The results of displacement show that the displacements increase with the period and with the story height in a base isolated building.
9. An increase in the period of isolation increases the bearing displacement; however, it decreases superstructure acceleration.
10. The absolute displacements of the upper floors of a structure with isolation are approximately 10 times that of the corresponding floors of a structure without isolation.
11. The absolute displacements of the a with base isolation are much larger than those with a fixed base; however, the relative floor displacements of a base isolated structure are much lower than that of a fixed-base structure.
12. The amplitudes of the acceleration responses of the structure with base isolation is much lower than that of a structure with a fixed base.
13. Lateral storey displacements are required to be further reduced and the installation of velocity in a structure should be considered.
14. The isolation technique broadens the choice of architectural forms and structural materials and it reduces structural and non-structural damage.
15. Displacement, velocity and acceleration of the storeys are remarkably reduced with an increase in the stiffness of the structure.
16. The resulting displacements increased with time, specifically the displacement of the last storey of a base isolated structure.
17. Hybrid isolation systems (rubber layers and steel plates) reduce efficiency as far structural drift, isolated reductions, higher flexibility and base shear are concerned.
18. The results show that isolation is was a better technique and it should be preferred in order to protect a structure from massive damage.

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RESUME

Salah Mustafa A. Almusbahi was born in Tripoli, Libya in 1976 where he accomplished his elementary education. He completed high school education in Grabouli High instuit School, after that, he started the undergraduate program at Grabouli High Institute, Department of Power Section in 2000. In 2004, he started assignment as a Research Assistant at Belgradei University, Department of Applied Section, and faculty of engineering to complete M.Sc.degree. Later, He moved to Karabük University, where he has been still working as a Ph.D. student.

In addition to his academic career, he has gained substantial experience while working for Almergeb University, Libya.

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