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Study of Seismic Isolation in Reinforced Concrete Buildings: Practical Application and Structural Behavior

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Abstract:
This research examines the concept and practical application of seismic base isolation in reinforced concrete buildings as an effective strategy to reduce earthquake-induced forces. The study highlights how base isolation systems—particularly elastomeric bearings, lead rubber bearings (LRB), and high-damping rubber bearings (HDRB)—function by decoupling the structure from ground motion, increasing the fundamental period of vibration, and reducing seismic acceleration and damage.
The research reviews pioneering experimental work conducted at the Earthquake Engineering Research Center (EERC) at UC Berkeley, where isolation bearings demonstrated up to tenfold reductions in structural acceleration. It also documents successful real-world applications in the United States, Japan, New Zealand, and other seismic regions, showing superior performance of isolated buildings during major earthquakes such as the 1994 Northridge and 1995 Kobe earthquakes.
The study provides detailed technical insights into the mechanical behavior, load capacity, durability, damping mechanisms, and structural response of various isolator types. It concludes that seismic isolation significantly enhances building safety, preserves structural integrity, protects internal contents, and ensures post-earthquake operability, making it an economical and reliable solution for critical and essential facilities.

Keywords: Seismic Base Isolation, Lead Rubber Bearing (LRB), High Damping Rubber Bearing (HDRB), Period Elongation, Structural Resilience, Energy Dissipation, Post-earthquake Operability, Seismic Demand Reduction, software Sap2000v20.

دراسة تقنيات العزل الزلزالي في المباني الخرسانية وتأثيرها على السلوك الإنشائي

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الملخص
يتناول هذا البحث واحدة من أهم التقنيات الحديثة في الهندسة الزلزالية، وهي تقنية العزل الزلزالي في المباني الخرسانية، باعتبارها الحل الأكثر فاعلية للحد من تأثير الهزّات الأرضية على المنشآت. تقوم هذه التقنية على فصل المبنى عن الأساسات باستخدام نظم مرنة مثل الروافع المطاطية (Elastomeric Bearings) أو الروافع المطاطية المحتوية على الرصاص (LRB)، ما يؤدي إلى تقليل انتقال القوى والتسارع إلى المبنى، وإطالة فترة اهتزازه وبالتالي خفض شدة الاستجابة الزلزالية. يرصد البحث تطور العزل الزلزالي منذ بداياته في مركز أبحاث الهندسة الزلزالية EERC في جامعة كاليفورنيا، حيث أثبتت التجارب قدرة هذا النظام على تخفيض التسارع بما يصل إلى عشرة أضعاف مقارنة بالتصميم التقليدي. كما يستعرض نجاحات تطبيقه في الولايات المتحدة واليابان ونيوزيلندا والصين، وخاصة الأداء المميز للمباني المعزولة خلال زلازل مدمرة مثل زلزال نورثريدج 1994 وزلزال كوبي 1995.

ويتناول البحث الأسس النظرية للعزل، والتي تشمل:

- إطالة فترة الاهتزاز لخفض قوى القص القاعدي.
- زيادة التخميد للحد من الإزاحات.
- توفير صلابة عند الأحمال الخدمية كالعوامل الريحية.
- سلوك العناصر المطاطية تحت الأحمال الدورية، وخصائص المتانة ومقاومة الاهتراء.

كما يقدم تحليلاً تفصيلياً لأنواع العوازل، وخاصة:

- عوازل المطاط الطبيعي والصناعي،
- عوازل الرصاص المطاطي LRB،
- العوازل عالية التخميد HDRB،

ويستعرض مزايا كل نوع وخصائصه الهندسية وأثره المباشر في تحسين أداء المبنى أثناء الزلازل.

ويخلص البحث إلى أن العزل الزلزالي لا يرفع فقط قدرة المبنى على مقاومة الأحمال الديناميكية، بل يضمن أيضاً سلامة محتوياته واستمرارية عمله بعد الزلزال، مما يجعله خياراً مثالياً للمستشفيات والمنشآت الحيوية. وتُظهر النتائج أن هذا النظام يجمع بين الفاعلية التقنية والجدوى الاقتصادية مقارنة بطرق التدعيم التقليدية، خاصة في المناطق متوسطة وعالية الخطورة الزلزالية.

الكلمات المفتاحية: العزل الزلزالي للقاعدة، عوازل الرصاص والمطاط (LRB)، عوازل المطاط عالي التخميد (HDRB)، إطالة الزمن الدوري، المرونة الإنشائية، تبديد الطاقة، استمرارية التشغيل بعد الزلزال، تقليل الطلب الزلزالي، برنامج ساب v202000.

1. Introduction

In recent years base isolation has become an increasingly applied structural design technique for buildings and bridges in highly seismic areas. Many types of structures have been built using this approach, and many others are in the design phase or under construction. Most of the completed buildings and those under construction use rubber isolation bearings in some way in the isolation system.

The ideas behind the concept of base isolation are quite simple. There are two basic types of isolation systems. The system that has been adopted most widely in recent years is typified by the use of elastomeric bearings, the elastomer made of either natural rubber or neoprene. In this approach, the building or structure is decoupled from the horizontal components of the earthquake ground motion by interposing a layer with low horizontal stiffness between the structure and the foundation. This layer gives the structure a fundamental frequency that is much lower than its fixed-base frequency and also much lower than the predominant frequencies of the ground motion. The first dynamic mode of the isolated structure involves deformation only in the isolation system, the structure above being to all intents and purposes rigid. The higher modes that will produce deformation in the structure are orthogonal to the first mode and consequently also to the ground motion. These higher modes do not participate in the motion, so that if there is high energy in the ground motion at these higher frequencies, this energy cannot be transmitted into the structure. The isolation system does not absorb the earthquake energy, but rather deflects it through the dynamics of the system. This type of isolation works when the system is linear and even when undamped; however, some damping is beneficial to suppress any possible resonance at the isolation frequency.

The second basic type of isolation system is typified by the sliding system. This works by limiting the transfer of shear across the isolation interface. Many sliding systems have been proposed and some have been used. In China there are at least three buildings on sliding systems that use a specially selected sand at the sliding interface. A type of isolation containing a lead-bronze plate sliding on stainless steel with an elastomeric bearing has been used for a nuclear power plant in South Africa [1]. The friction-pendulum system is a sliding system using a special interfacial material sliding on stainless steel and has been used for several projects in the United States, both new and retrofit construction.

To minimize the transmission of potentially damaging earthquake ground motions into a structure is achieved by the introduction of flexibility at the base of the structure in the horizontal direction while at the same time introducing damping elements to restrict the amplitude or extent of the motion caused by the earthquake somewhat akin to shock absorbers. In recent years this relatively new technology has emerged as a practical and eco- nomic alternative to conventional seismic strengthening. This concept has received increasing academic and professional attention and is being applied to a wide range of civil engineering structures. To date there are several hundred buildings in Japan, New Zealand, United States, India which use seismic isolation principles and technology for their seismic design.

2. Lecturer view of Research at EERC

Research on the development of natural rubber bearings for isolating buildings from earthquakes began in 1976 at the Earthquake Engineering Research Center (EERC) (now PEER, the Pacific Engineering Research Center) of the University of California at Berkeley. The initial research program was a joint effort by EERC and the Malaysian Rubber Producers Research Association (MRPRA), U.K. The program was funded by MRPRA through a number of grants over several years, with later funding provided by the National Science Foundation and the Electric Power Research Institute. Professor James M. Kelly directed the research at EERC, which included considerable theoretical and experimental contributions by graduate students.

Although not an entirely new idea at the time—a few methods using rollers or sliders had been proposed—the concept of base isolation was considered to be very impractical by most of the structural engineering profession. The research project began with a set of hand-made bearings of extremely low-modulus rubber used with a simple three-story, single-bay, 20-ton model. Shaking table tests showed that isolation bearings could bring about reductions in acceleration by factors of as much as ten when compared to those of conventional design and that, as predicted, the model would respond as a rigid body with all deformation concentrated in the isolation system. It was also clear that a certain degree of damping was needed in the system and that the scale of the model was too small to allow more practical rubber compounds to be used.

In 1978, a more convincing demonstration of the isolation concept was achieved with a more realistic five-story, three-bay model weighing 40 tons and by using damping-enhanced bearings made by commercial techniques. A strong interest throughout the EERC research program was in the influence of isolation on the response of equipment and contents in a structure, which tend to sustain more damage when conventional methods of seismic-resistant design are used and which, in many buildings, are much more costly than the structure itself. An extensive series of tests on the five-story frame demonstrated that isolation with rubber bearings could provide very substantial reductions in the accelerations experienced by internal equipment, exceeding the reductions experienced by the structure. However, the same tests showed that when additional elements (such as steel energy-absorbing devices, frictional systems, or lead plugs in the bearings) were added to the isolation system to increase damping, the reductions in acceleration to the equipment were not achieved because the added elements also induced responses in the higher modes of the structure, affecting the equipment. It became clear that the optimum method of increasing damping was to provide it in the rubber compound itself. This method was applied later in the compound developed by MRPRA and used in the first base-isolated building in the United States, described below[2].

2.1 U.S. Applications

The first base-isolated building in the United States is the Foothill Communities Law and Justice Center, a $30 million legal services center in Rancho Cucamonga San Bernardino County, about 97 km (60 miles) east of downtown Los Angeles. Completed in 1985, the building is four stories high with a full basement and sub-basement for the isolation system, which consists of 98 isolators of multilayered natural rubber bearings reinforced with steel plates. The superstructure of the building has a structural steel frame stiffened by braced frames in some bays.

Foothill Communities Law and Justice Center. Photo: I. D. Aiken.

The building is located 20 km (12 miles) from the San Andreas fault. San Bernardino County, the first in the U.S. to have a thorough earthquake preparedness program, asked that the building be designed for a Richter magnitude 8.3 earthquake, the maximum credible earthquake for that site. The design selected for the isolation system, which accounted for possible torsion, incorporated a maximum horizontal displacement demand of 380 mm (15 in.) in the isolators at the corners of the building. Tests of full-scale sample bearings verified this capacity.

The highly filled natural rubber from which the isolators are made, developed as part of the EERC research program, has mechanical properties that make it ideal for a base isolation system. The shear stiffness of this rubber is high for small strains but decreases by a factor of about four or five as the strain increases, reaching a minimum value at a shear strain of 50 percent. For strains greater than 100 percent, the stiffness begins to increase again, providing a fail-safe action under a very high load. The damping follows the same pattern but less dramatically, decreasing from an initial value of 20 percent to a minimum of 10 percent and then increasing again. The design of the system assumes minimum values of stiffness and damping and a linear response. The high initial stiffness is invoked only for wind load design and the large strain response only for fail-safe action[3].

This high-damping rubber system was also adopted for the Fire Department Command and Control Facility (FCCF) of Los Angeles County, completed in 1990. (The same type of high-damping rubber bearing was also used for the Italian telephone company, S.I.P., Ancona, Italy, the first modern base-isolated building in Europe.) The FCCF building houses the computer systems for the emergency services of the county and is therefore required to remain functional after an extreme event.

Fire Department Command and Control Facility. Photo: I.D. Aiken

The decision to use base isolation for this project was reached by comparing conventional and isolation schemes designed to provide the same degree of protection. In most projects, the isolation design costs five percent more. Not only was the isolation design estimate 6 percent less in this case but is less for any building when equivalent levels of protection are considered. Furthermore, these costs are first costs. Life-cycle costs are even more favorable. Also noteworthy is that the conventional code design requires only a minimal level of protection, that the structure not collapse; whereas isolation design provides a higher level of protection.

The University of Southern California Teaching Hospital in eastern Los Angeles is an eight-story concentrically braced steel frame supported on 68 lead rubber isolators and 81 elastomeric isolators. The building was instrumented by the California Strong Motion Instrumentation Program soon after its completion in 1991. The foundation system consists of spread footings and grade beams on rock. Because of functional requirements, both the building plan and elevation are highly irregular with numerous setbacks over the height. Two wings at either side of the building are connected through what is referred to as the "necked-down" portion of the building, and in the original fixed-base design the irregular configuration led to both coupling between the lateral and torsional vibration modes and very large shear force demands in the slender region between the two rings. (Even in the isolated design steel trusses are required to carry the shears in the necked-down region.) These were two of the main reasons that seismic isolation was eventually chosen for this structure.

University of Southern California University Hospital. Photo: P. W. Clark.

The University of Southern California (USC) Teaching hospital was 36 km (23 miles) from the epicenter of the M_w 6.8 1994 Northridge earthquake. The peak ground acceleration outside the building was 0.49 g, and the accelerations inside the building were around 0.10 to 0.13 g. In this earthquake the structure was effectively isolated from ground motions strong enough to cause significant damage to other buildings in the medical center. The records obtained from the USC hospital are particularly encouraging in that they represent the most severe test of an isolated building to date.

2.2 Base Isolation in Japan

After a slow start, base isolation research and development in Japan increased rapidly. The first large base-isolated building was completed in 1986. Although such buildings in Japan require special approval from the Ministry of Construction, as of June 30, 1998, 550 base-isolated buildings had been approved.

Base isolation has advanced rapidly in Japan for several reasons. The expenditure for research and development in engineering is high with a significant amount designated specifically for base isolation; the large construction companies aggressively market the technology; the approval process for constructing a base-isolated building is a straightforward and standardized process; and the high seismicity of Japan encourages the Japanese to favor the long-term benefits of life safety and building life-cycle costs when making seismic design decisions[4]. The system most commonly used in the past has been natural rubber bearings with mechanical dampers or lead-rubber bearings. Recently, however, there has been an increasing use of high-damping natural rubber isolators. There are now several large buildings that use these high-damping bearings: an outstanding example is the computer center for the Tohoku Electric Power Company in Sendai, Miyako Province.

Tohoku Electric Power Company, Japan. Photo: P. W. Clark

Currently the largest base-isolated building in the world is the West Japan Postal Computer Center, located in Sanda, Kobe Prefecture. This six-story, 47,000 m square (500,000 ft square) structure is supported on 120 elastomeric isolators with a number of additional steel and lead dampers. The building, which has an isolated period of 3.9 sec, is located approximately 30 km (19 miles) from the epicenter of the 1995 Hyogoken Nanbu (Kobe) earthquake, and experienced severe ground motion. The peak ground acceleration under the isolators was 400 cm/sec square (0.41 g) but was reduced by the isolation system to 127 cm/sec square (0.13 g) at the sixth floor. The estimate of the displacement of the isolators is around 12 cm (4.8 in.). A fixed-base building adjacent to the computer center experienced some damage, but there was no damage to the isolated building.

The use of isolation in Japan continues to increase, especially in the aftermath of the Kobe earthquake. As a result of superior performance of the West Japan Postal Computer Center, there has been a rapid increase in the number of permits for base-isolated buildings, including many apartments and condominiums.

3. SEISMIC ISOLATION COMING TO REALITY

Seismic isolation is intended to prevent earthquake damage to structures, buildings and building contents, One type of seismic isolation system employs load bearing pads, called isolators. They are located strate- gically between the foundation and the building structure and are designed to lower the magnitude and frequency of seismic shock permitted to enter the building. They provide both spring and energy absorbing characteristics.

Figure 1 illustrates the behavior change of structure without isolator and with isolator incorporation.

The first seismic isolation system was proposed by Dr. Johannes Calantarients, an English medical doctor, in 1909. His diagrams show a building separated from its foundation by a layer of talc which would isolate the main structure from seismic shock. The oldest base isolated structure of the world, Mausoleum of Cyrus, is shown in Figure 2.This technology can be used both for new structural design and seismic retrofit. In process of seismic retrofit, some of the most prominent U.S. monuments like Pasadena City Hall, San Francisco City Hall, Salt Lake City and County Building or LA City Hall. The seismic rehabilitation of the Los Angeles City Hall is a landmark event in the City's history.

For Los Angeles City Hall (Figure 3a), in process of seismic upgrading, this high- rise building was placed atop a mechanical system of isolators, sliders and dampers called base isolation technology. Later on a few famous isolated buildings have also been shown in Figure 3. Bhuj Hospital (Figure3b), New Zealand Assembly Library (Figure 3c) and New Zealand Parliament (Figure 3d) have been erected on Lead Rubber bearing type base isolator. Isolation system was also inserted at Te Papa Museum of New Zealand (Figure 3e). Figure 3f shows the practical construction of inserting seismic isolation system in Te Papa Museum building.

Early concerns were focused on the fear of uncon- trolled displacements at the isolation interface, but these have been largely overcome with the successful develop- ment of mechanical energy dissipaters. When used in combination with a flexible device, an energy dissipater can control the response of an isolated structure by limiting both the displacements and the forces. Interest in base isolation as an effective means of protecting structures from earthquakes has therefore, been revived in recent years.The following are the advance developments (Kelly,1998) that have enabled base isolation to be a practical reality.

(a) The design and manufacture of high quality isolation bearings that are used to support the weight of the structure and at the same time, release it from earthquake induced forces.

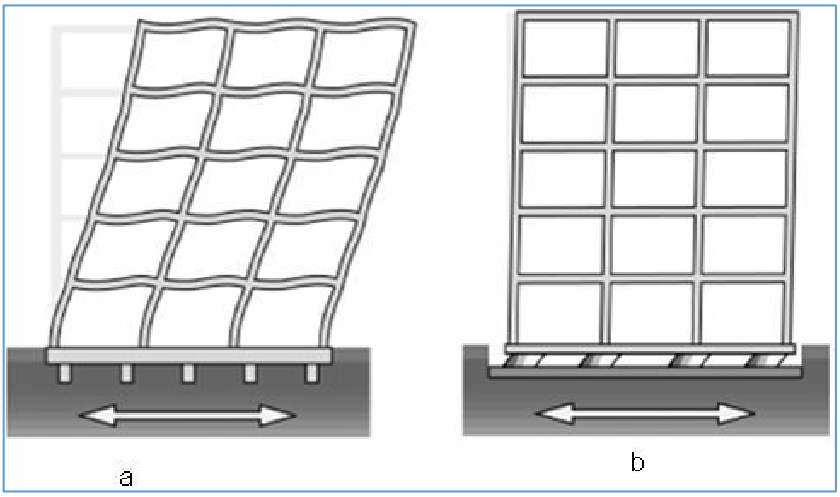


Figure 1. Behavior change while using isolator. (a) Conventional structure (b) base -isolated structure.

Figure 2. Mausoleum of Cyrus, the oldest base-isolated structure in the world.

(b) The design and manufacture of mechanical energy dissipaters (absorbers) that are used to reduce the movement across the bearings to practical and acceptable levels (4 to 6 inches) and to resist wind loads (c) The development and acceptance of computer software for the analysis of base-isolated structure which includes nonlinear material properties and the time- varying nature of the earthquake loads.

(d) The ability to perform shaking table tests using real recorded earthquake ground motions to evaluate the performance of structures and provide results to validate computer modeling techniques.

(e) The development and acceptance procedures for estimating site-specific earthquake ground-motions for different return periods [6].

4. BASE ISOLATION SYSTEM

Basic elements of base isolation Seismic Isolation increases the fundamental period of vibration so that the structure is subjected to lower earthquake forces. However, the reduction in force is accompanied by an increase in displacement demand, which must be accommodated within the flexible

Figure 3. Some Renowned Base-isolated Structures, (a) Los Angeles City Hall, USA, (b) Bhuj Hospital, Gujrat, India, (c) New Zealand Assembly Library, (d) New Zealand Parliament, (e) Te Papa Museum of New Zealand, (f) Te Papa during Incorporation of Isolator.

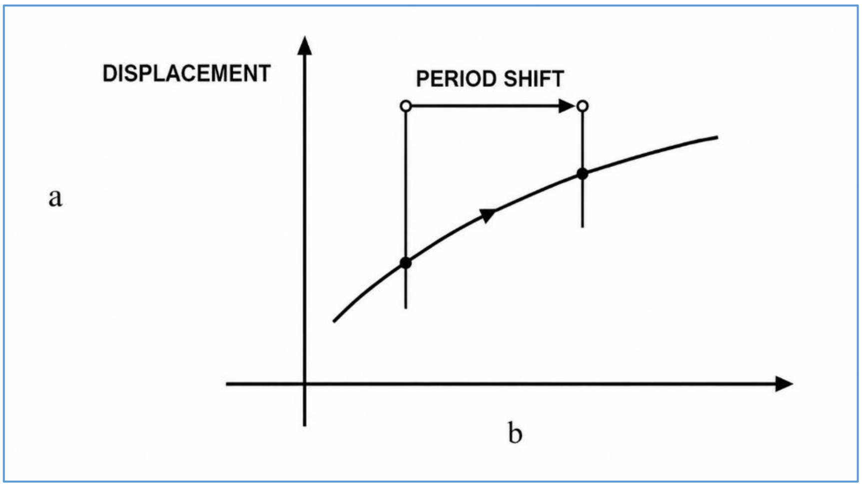


Figure 4. Impact of period elongation obtained by seismic isolation on accelerations. (a) Acceleration response spectrum, (b) displacement response spectrum and displacements of a structure

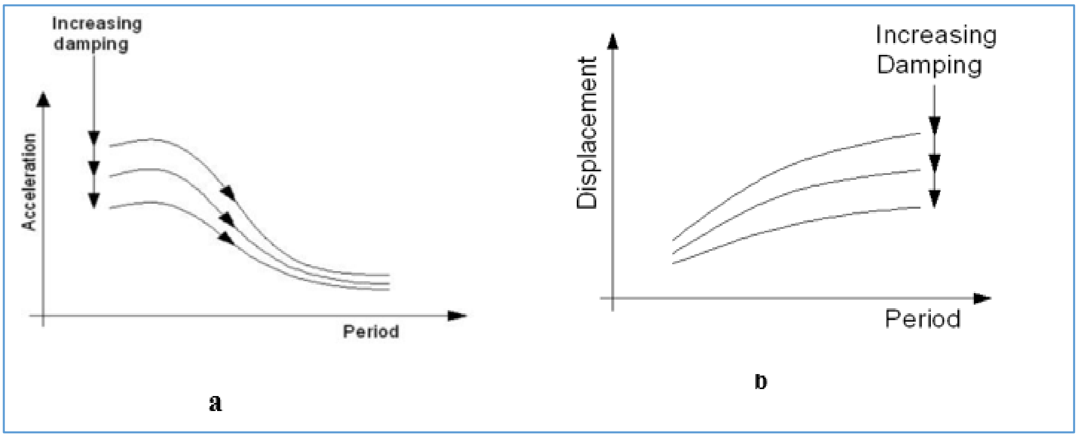


Figure 5. Acceleration and displacement response Spectrum for increasing damping. (a) Acceleration RS, (b) Displacement RS.

Mount, Furthermore, longer period buildings can be lively under service loads. The following are three basic elements in any practical isolation system (Skinner et al., 1993), they are:

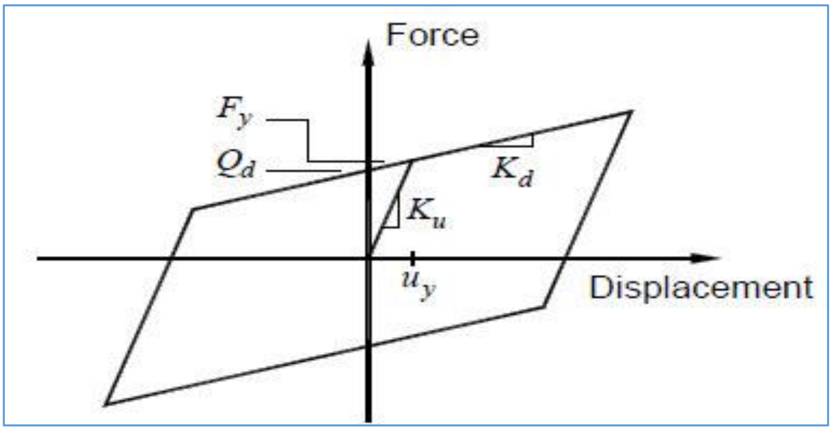


Figure 6. Idealized force-displacement (Hysteresis) Loop.

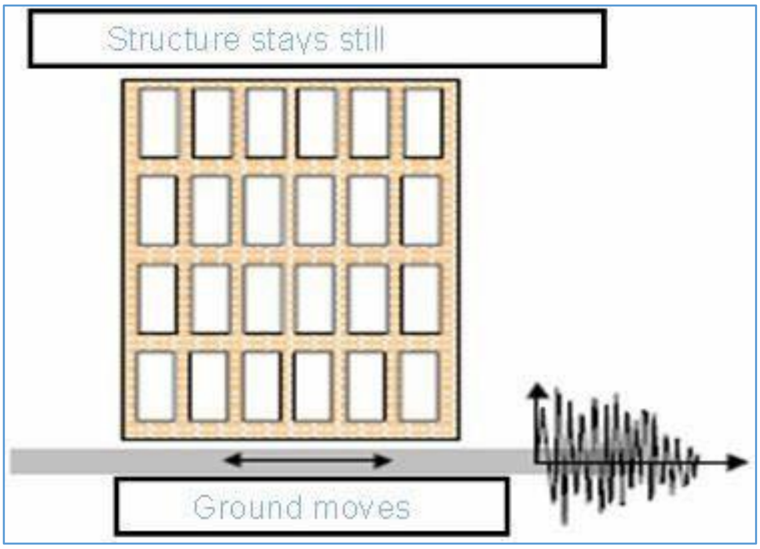


Figure 7. Base isolation strategy.

deflections across the flexible mounting can be limited to a practical design level.
3. A means of providing rigidity under low (service) load levels such as wind and braking force

Flexibility: Due to additional flexibility the period of structure is elongated. From the acceleration response curve shown in Figure 4a, it may be observed that reductions in base shear occur as the period of vibration of the structure is lengthened. The extent to which these forces are reduced is primarily dependent on the nature of the earthquake ground motion and the period of the non-isolated structure.

Energy dissipation: Additional flexibility needed to lengthen the period of the structure will give rise to large relative displacement across the flexible mount.
Figure 4b shows an idealized displacement response curve from which displacements are seen to increase period (flexibility). Large relative displacements can be controlled if substantial additional damping is introduced into the structure at the isolation level. This is shown schematically in Figure 5. Also shown schematically in this figure is the smoothening effect of higher damping.
One of the most effective means of providing a substantial level of damping is through hysteric energy dissipation. The hysteric refers to the offset between the loading and unloading curves under cyclic loading.
Figure 6 shows an idealized force-displacement loop where the enclosed area is a measure of the energy dissipated during one cycle of motion.

Rigidity under low lateral loads: While lateral flexibility is highly desirable for high seismic loads, it is clearly undesirable to have a structural system which will vibrate perceptibly under frequently occurring loads such as wind loads or braking loads. Mechanical energy dissipaters may be used to provide rigidity at these service. [10]

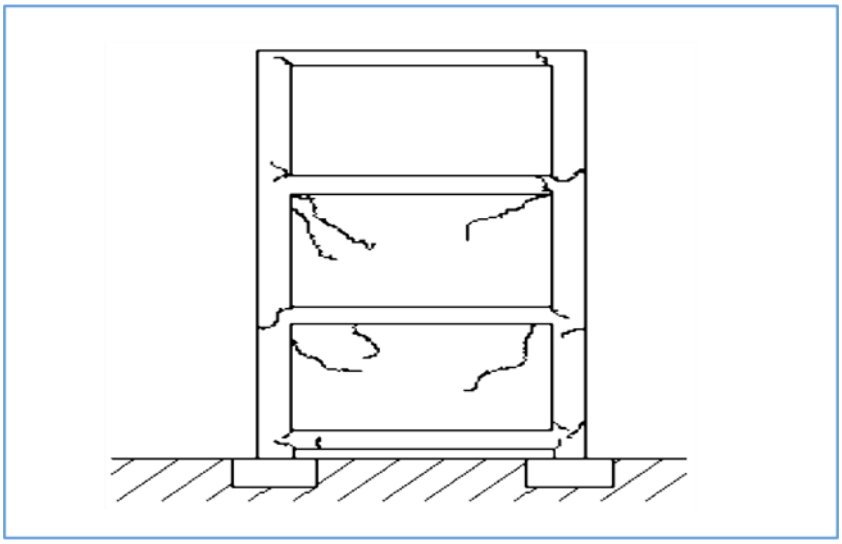


Figure 8. Failure pattern of a fixed based structure due to lateral seismic loading.

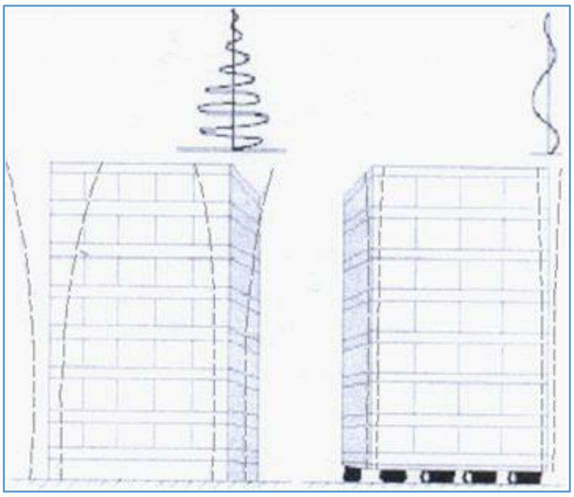


Figure 9. Fixed base and isolated base.

5. Fundamental concepts of base isolation

The term base isolation uses the word a) isolation in its meaning of the state of being separated and b) base as a part that supports from beneath or serves as a foundation for an object or structure. As suggested in the literal sense, the structure (a building, bridge or piece of equipment) is separated from its foundation. The original terminology of base isolation is more commonly replaced with seismic isolation nowadays, reflecting that in some cases the separation is somewhere above the base – for example, in a building the superstructure may be separated from substructure columns. In another sense, the term seismic isolation is more accurate anyway in that the structure is separated from the effects of the seism, or earthquake (Kelly, 2001).

The only way a structure can be supported under gravity is to rest on the ground. Isolation conflicts with this fundamental structural engineering requirement.

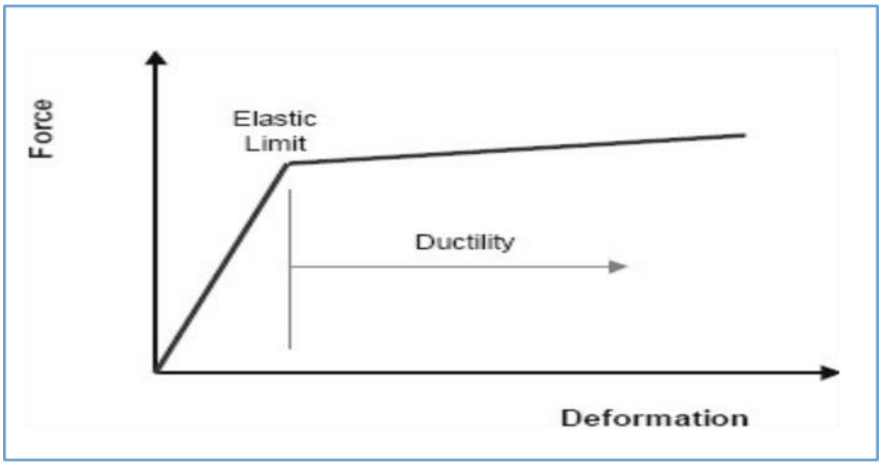


Figure 10. Ductility: deformation beyond elastic limit.

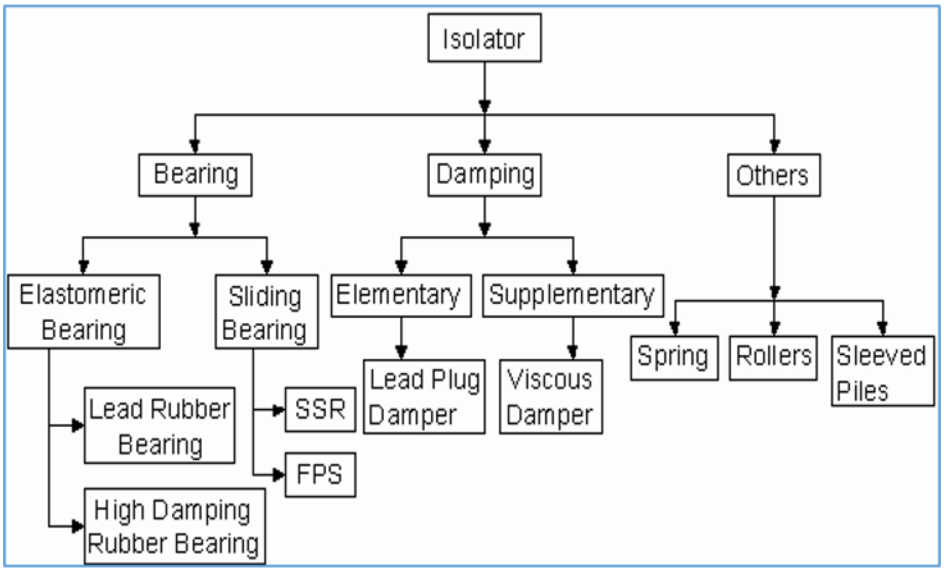


Figure 11. Schematic Diagram showing various types of Isolators used throughout the world.

1. A flexible mounting so that the period of vibration of the building is lengthened sufficiently to reduce the force response.
2. A damper of energy dissipater so that the relative

How can the structure be separated from the ground for earthquake loads but still resist gravity? It is practical isolation systems that provide a compromise between attachment to the ground to resist gravity and separation from the ground to resist earthquakes (Figure 7). Seismic isolation is a means of reducing the seismic demand on the structure.

Hence, "base isolation" or, seismic isolation separates upper structure from base or, from down structure by changing of fix joint with flexible one (Figure 10).

Increasing of flexibility is done by the insertion of additional elements in structure, known as isolators. Usually, these isolators are inserted between upper structure and foundation (Figure 12). Seismic isolation system absorbs larger part of seismic energy. Therefore, vibration effects of soil to upper structure are drastically reduced. Figure 8 shows the failure pattern of a "fixed based" structure due to seismic loading.

But in case of isolated buildings as the ground moves, inertia tends to keep structures in place resulting in the imposition of structure with large displacements in different stories (Figure 9: left figure: dashed portion indicating displacements due to seismic loading).

For base isolated structure the situation is quite

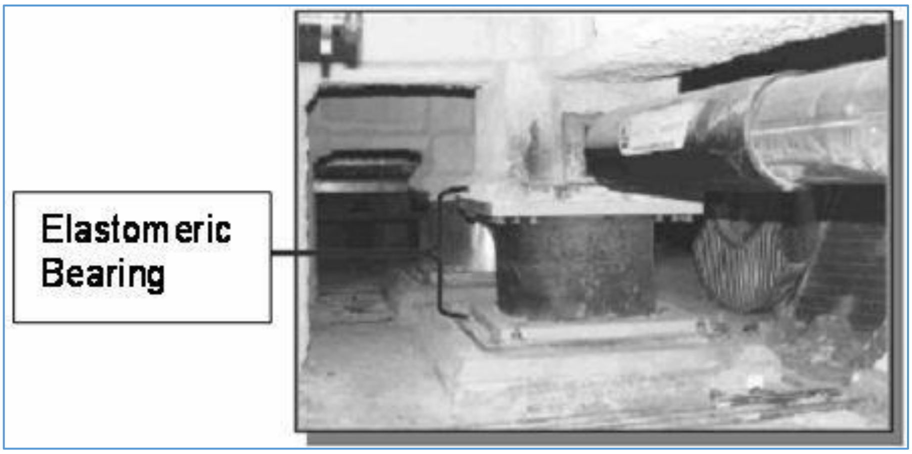


Figure 12. Installed elastomeric bearing.

different. In such cases, the whole upper structure gets a displacement (which naturally remains in limits) and the relative displacement of different stories is so small that the structure can withstand a comparatively high seismic tremor with a low seismic loading in a safe, efficient and economic manner [13].

A high proportion of the world is subjected to earthquakes and society expects that structural engineers will design our buildings so that they can survive the effects of these earthquakes. As for all the load cases encountered in the design process, such as gravity and wind, should work to meet a single basic equation: CAPACITY > DEMAND.

Earthquakes happen and are uncontrollable. So, in that sense, we have to accept the demand and make sure that the capacity exceeds it. The earthquake causes inertia forces proportional to the product of the building mass and the earthquake ground accelerations. As the ground accelerations increases, the strength of the building, the capacity, must be increased to avoid structural damage. But it is not practical to continue to increase the strength of the building indefinitely.

In high seismic zones the accelerations causing forces in the building may exceed one or even two times the acceleration due to gravity, g. It is easy to visualize the strength needed for this level of load – strength to resist 1 g means than the building could resist gravity applied sideways, which means that the building could be tipped on its side and held horizontal without damage.

Designing for this level of strength is not easy, nor cheap. So, most codes allow engineers to use ductility to achieve the capacity. Ductility is a concept of allowing the structural elements to deform beyond their elastic limit in a controlled manner (Figure10). Beyond this limit, the structural elements soften and the displacements increase with only a small increase in force.

The elastic limit is the load point up to which the effects of loads are non- permanent; that is, when the load is removed the material returns to its initial condition. Once this elastic limit is exceeded changes occur. These changes are permanent and non-reversible when the load is removed.

A design philosophy focused on capacity leads to a choice of two evils:

1. Continue to increase the elastic strength. This is expensive and for buildings leads to higher floor accelerations. Mitigation of structural damage by further strengthening may cause more damage to the contents than would occur in a building with less strength.
2. Limit the elastic strength and detail for ductility. This approach accepts damage to structural components, which may not be repairable.

6. RECOGNITION OF ISOLATION TYPES

Many types of isolation system have been proposed and have been developed to varying stages, with some remaining no more than concepts and others having a long list of installed projects. A discussion of generic types of system and focus on different types (especially rubber bearing) of isolators along with their characteristics is provided subsequently.

Types of isolators the development of isolators ensured
the properties

6.1 Elastomeric (rubber) bearings

Rubber bearings are formed of horizontal layers of natural or synthetic rubber in thin layers bonded between steel plates. The steel plates prevent the rubber layers from blown up or busting. In such mechanism the bearing is capable to support higher vertical loads with only smaller deflection (typically 1 to 3 mm under full gravity load).

The internal steel layers do not restrict horizontal deformations of the rubber layers in shear. So, the bearings are much more flexible under lateral loads than vertical loads. This is why; the bearing works as a flexible unit.

6.2 Characteristics of rubber isolator

As described earlier, isolation system works with the principle that a rigid mass is isolated from a flexible supporting structure.

Optimum isolation of a building from ground may be achieved by choosing a rubber bearing isolator based on the knowledge of its static and dynamic characteristics determined from laboratory experiments. For this reason, understanding the properties of rubber isolators is necessary for the vibration analysis. Some of the important properties are as follows.

6.3 Durability under cyclic loading

Rubber isolator remains more or less stable under cyclic loading. Results of cyclic displacement test applied, to a rubber isolator shows that at a speed equivalent to an actual seismic event the friction factor remains stable. Figure 15 shows a typical friction factor versus number of cycles in a cyclic loading test of rubber isolator. The figure represents that rubber isolator is durable. There are mainly two types of Rubber Bearing. They are LRB and HDRB.

6.4. High damping rubber bearing (HDRB)

HDRB is one type of elastomeric bearing. This type of bearing consists of thin layers of high damping rubber and steel plates built in alternate layers as shown in Figure 17. The vertical stiffness of the bearing is several hundred times the horizontal stiffness due to the presence of internal steel plates. Horizontal stiffness of the bearing is controlled by the low shear modulus of elastomer while steel plates provides high vertical stiffness as well as prevent bulging of rubber. High vertical stiffness of the bearing has no effect on the horizontal stiffness. The damping in the bearing is increased by adding extra-fine carbon block, oils or resins.

These bearings are fully developed as commercial products whose main application has been for bridges and buildings. The RB system consists of al- ternating layers of rubber and steel with the rubber being vulcanized to the steel plates for the horizontal flexibility and the vertical stiffness. The dominant feature of this device is the parallel action of spring and dashpot (Figure13). The equation of motion is stated as :

$$M\ddot{x}_b(t) + C_b\dot{x}_b(t) + K_b x_b(t) + \sum_{n=1}^{N} m_n a_n = -M\ddot{x}_g(t) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Where, C_b and K_b are damping and stiffness coeffi- cients of the RB system, respectively. The high-loss rubber has use for this device with high damping value and it calls as high damping rubber bearing (HDRB).

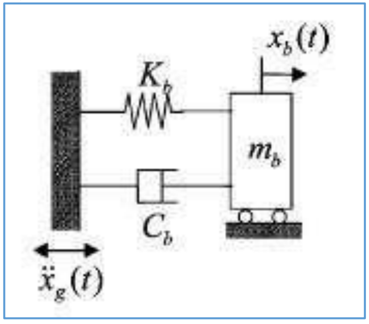


Figure 13. RB/HDRB model.

8.5 Lead rubber bearing (LRB)

This type of elastomeric bearings consist of thin layers of low damping natural rubber and steel plates built in alternate layers and a lead cylinder plug firmly fitted in a hole at its centre to deform in pure shear as shown in Figure 16. The LRB was invented in New Zealand in 1975 and has been used extensively in New Zealand, Japan and United States. The steel plates in the bearing force the lead plug to deform in shear.

This bearing provides an elastic restoring force and also, by selection of the appropriate size of lead plug, produces required amount of damping. The force deformation behavior of the bearing is shown in Figure

16. Performance of LRB is maintained during repeated strong earthquakes, with proper durability and reliability.

LRB mainly are of two shapes. One is conventional round and the other type is square. Though their basic function remains same, yet changes in shapes are advantageous in many occasions as economy concern, reduced size, stability and capacity for large deformation.

A lead-plug insert in the core of RBs. It provides hysteretic energy-dissipation; therefore, the damping required for a successful seismic isolation system can be incorporated in a single compact component with the RB system. Thus, one device is able to sup- port the structure vertically, to provide the horizontal flexibility together with the restoring force, and to provide the required hysteretic damping. To deter- mine properties of the LRB system, the bilinear model of characteristic curve is used. The effective stiffness coefficient, Keff, is obtained with reference to shear force versus displacement hysteresis loop (Figure14). In general, the concept of this effective val- ue is a gross approximation, but it works surprising- ly well.

The equation of motion, which uses the effective and equivalent values, is stated as:

$$M\ddot{x}_b(t) + C_{eq}\dot{x}_b(t) + K_{eff}x_b(t) + \sum_{n=1}^{N} m_n a_n = -M\ddot{x}_g(t)$$
…………………….……………….(2)

Where, Ceq is the equivalent linear damping coeffi-cient given by Eq. (3) and ξeq is the equivalent linear damping ratio given by Eq. (4), respectively.

$$C_{eq} = 2\xi_{eq}\sqrt{MK_{eff}}$$
……………………..…………………….………………….(3)

$$\xi_{eq} = \Delta E/(2\pi K_{eff}D_D^2)$$
…………………...………………………………………….(4)

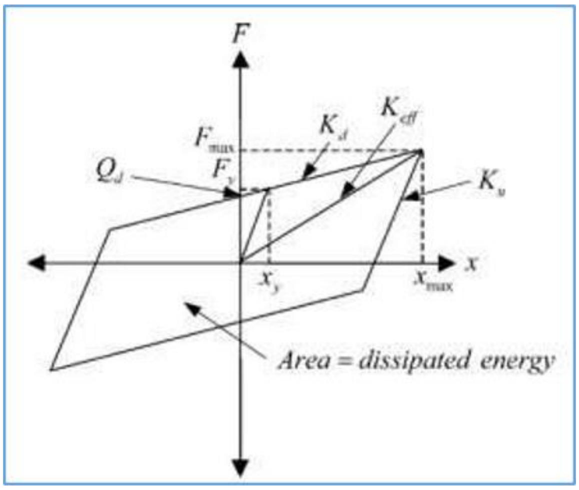


Figure14. Characteristic of LRB system.

7. SENSITIVITY ANALYSIS

7.1 Model description and assumptions

The floor slabs of the building are all modeled as solid slabs of 150mm thickness while walls are all having 200 mm thickness. Dead and live loads are given in Table (1). The building concrete compression resistance value, fc', is of 35MPa and the steel reinforcement yield stress, fy, is of 500MPa, see table (2).

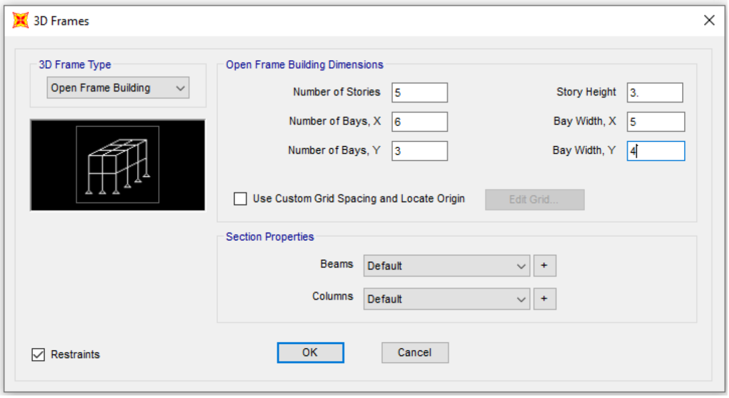
Table (1) Input floor Dead and Live load to SAP 2000 program.

Loads	Dead load	Floors:2.0 KN/m^2
	Live load	Floors:10 KN/m^2
	SD	15 KN/m
	Lat-load	50 KN

Table (2) Input parameters of the 5 Story building model

Materials	Concrete compression resistance Reinforcing yield stress	f_c'=35 MPa $f_{y=}$ 500 MPa
Dimensions	Beams	400 x 600 mm2
	walls width	d = 200 mm
	columns	400*400 mm

The geometry of the building is needed for the SAP2000 program and a plan view with marked axes is given in Figures (15) and (16) and define load cases for five-story building is given in Figures (17).



3D Frames

3D Frame Type: Open Frame Building

Open Frame Building Dimensions

Number of Stories: 5

Number of Bays, X: 6

Number of Bays, Y: 3

Story Height: 3.

Bay Width, X: 5

Bay Width, Y: 4

☐ Use Custom Grid Spacing and Locate Origin

Section Properties

Beams: Default

Columns: Default

☑ Restraints

Figure (15) Properties of Building as specified as in SAP2000.

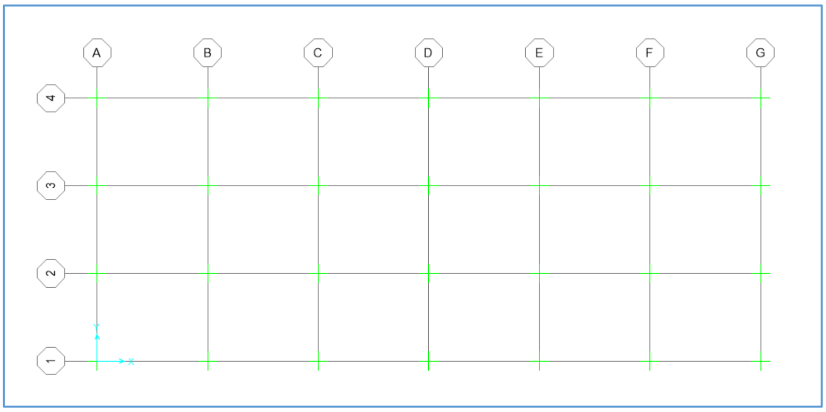
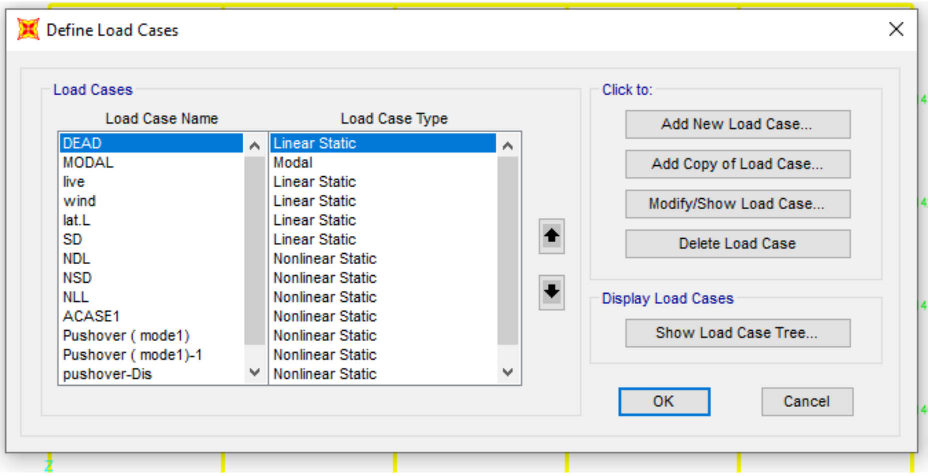


Figure (16) Plan view of the R.C. five-story building.



Load Case Name	Load Case Type
DEAD	Linear Static
MODAL	Modal
live	Linear Static
wind	Linear Static
lat.L	Linear Static
SD	Linear Static
NDL	Nonlinear Static
NSD	Nonlinear Static
NLL	Nonlinear Static
ACASE1	Nonlinear Static
Pushover (mode1)	Nonlinear Static
Pushover (mode1)-1	Nonlinear Static
pushover-Dis	Nonlinear Static

Figure (17) define load cases for five-story building.

For the performance analysis of two BIS models, three different models of steel frames have been considered (Table 3). For the low-rise to mid-rise models the 5 and 10 stories, building have been analyzed. Performance analysis and pushover analy- sis were carried out to find the number of plastic hinges and the performance level of each model for different type of base isolators.

Table 3. Specification of Models

Description	Model 1	Model 2
Fixed Base Models	5F	10F
Isolated Base Model	5I	10I
Columns shape	Rectangular	Rectangular
Connections	Fixed	Fixed
Design Code	FEMA 357	FEMA 357
Software	SAP2000	SAP2000
Height of stories	3m	3m
Length of spans	5m	5m

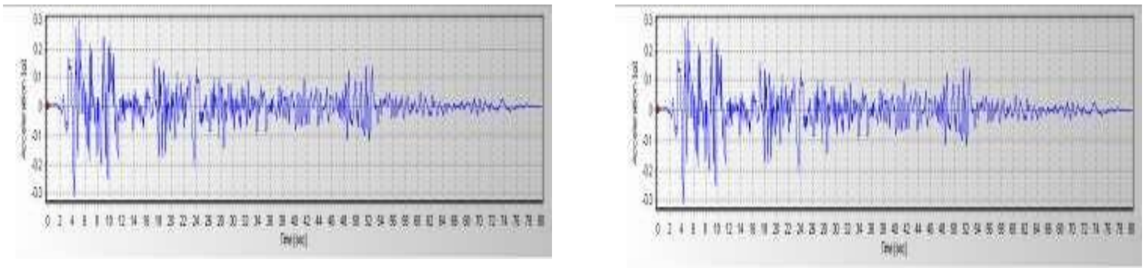
For the performance, analysis on variations in the de- sign parameters of BISs, a number of different earthquake excitations are used (Figuer18).

Among several major earthquake excitations, El CENTRO (1940), CAPE MENDOCINO (1992) and NORTHRIDGE (1994) earthquakes are used as the ground acceleration. These earthquake records have a variety of peak ground acceleration (PGA) and cover various forms of the frequency range. The El Centro time history is typical of those to be expected on the ground of moderate flexibility during a major earthquake. It must also be recognized that occasionally earthquakes give their strongest excitation at long periods

The finite element analysis software, SAP2000 has been used for both Static nonlinear Pushover Analysis (SNPA) and Nonlinear Time History Analysis (NTHA).

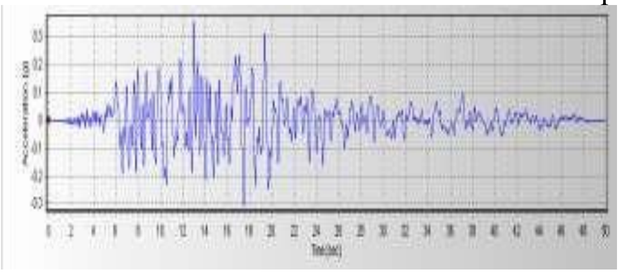
SNPA is used to check the behavior and find the different structural levels of performance based on

FEMA 357. Three levels of plastic behavior intro-duced as IO (Immediate Occupancy), LS (Life Safety), and CP (Collapse Prevention) are the basis in FEMA (Fig. 19).



Cape Mendocino Earthquake record, 1992

El Centro Earthquake record, 1940



Northridge Earthquake record, 1994

Figure 18 Time histories of different earthquakes

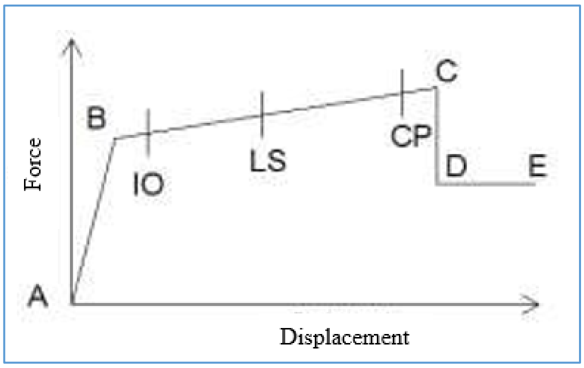


Figure 19. FEMA Force-Displacement relation

This is an essential analysis to find the proper level of structural strength for all models with different stories and for both fixed and BISs.

The parameters for the LRB have been selected from Robinson Company in New Zealand and HDRB from FIP Company in Italy (Table 4).

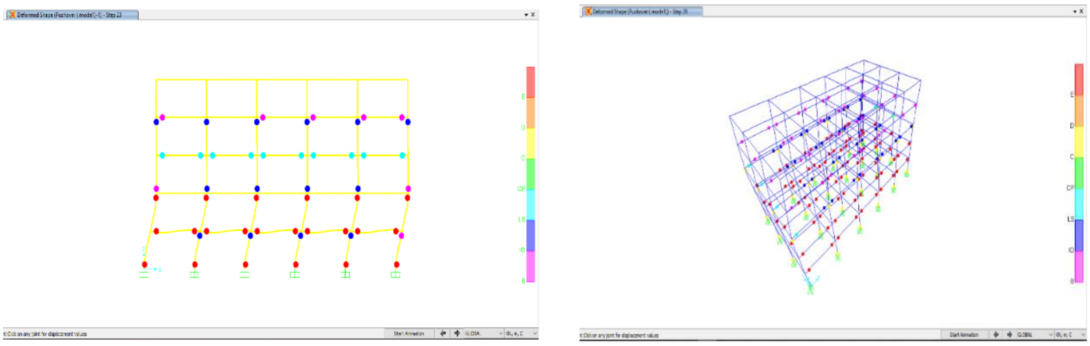
The designed values for BISs will show the similar conditions for behavior for both.

Table 4. Specification of BISs for 5 & 10 stories Bld.

Parameter	No. of Stories	LRB	HDRB
Effective Stiffness	5	2322 KN/m	3628.2 KN/m
Stiffness	10	808.6 KN/m	1468 KN/m
Fy	10	630 MPa	175.6 MPa
Effective Stiffness	10	4043.1 KN/m	7339.8 KN/m

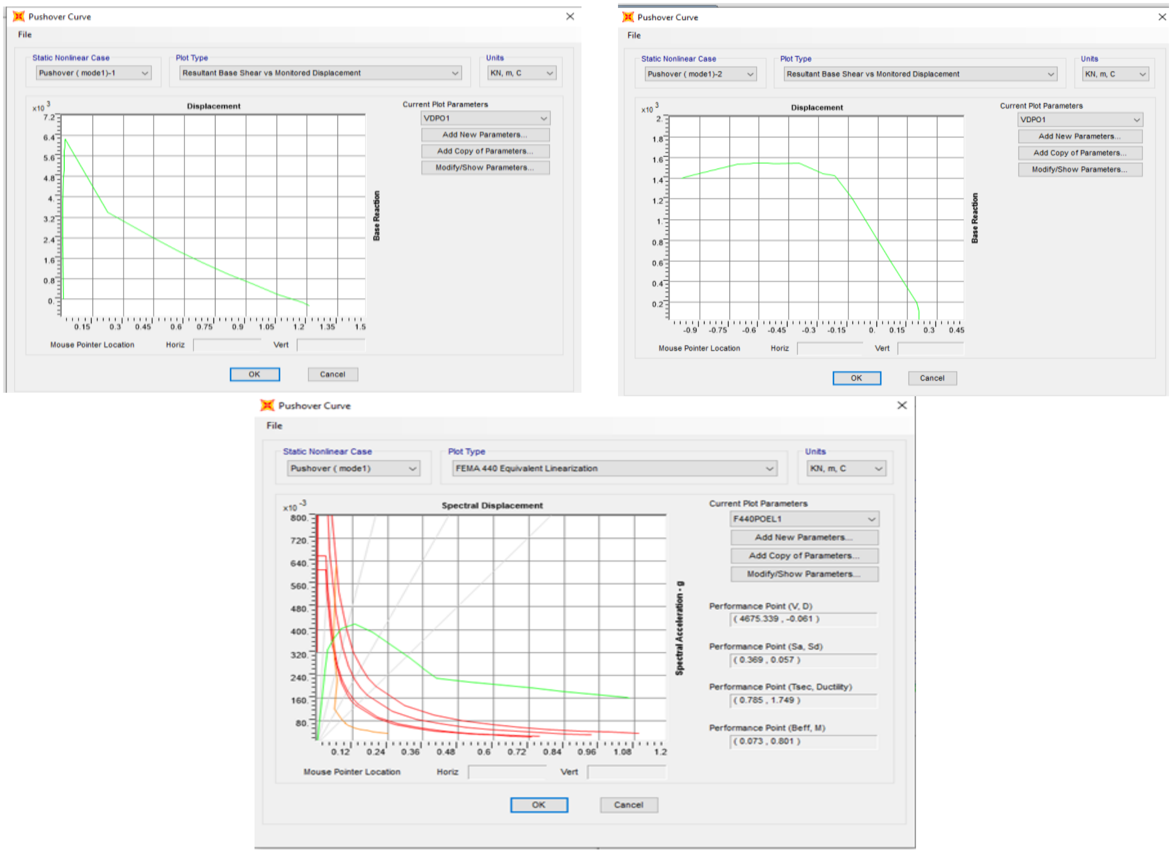
7.2 Static Nonlinear Pushover Analysis

All models have been designed based on codes and a sort of iterative SNPA have been carried out for each model with and without BISs to check their confidence and consistent assumption and proper section properties during different steps of incremental loading, and the frame hinges for 5, 10 stories as shown in figure 20 and deformation shap as shown in figure 21 . and pushover curve shown in figure 22.This analysis will show the IO and LS conditions for the frames in the same steps of loading. In addition, different Scenarios of SNPA have been considered to show the consistency in behavior Table 5 and Fig. 23



Figuer 20. deformatio shap pushover for 5,10 stories

Figuer 21 frame hinges for 5,10 stories



Static Nonlinear Case: Pushover (mode1)-1
Plot Type: Resultant Base Shear vs Monitored Displacement
Units: KN, m, C
Current Plot Parameters: VDPO1

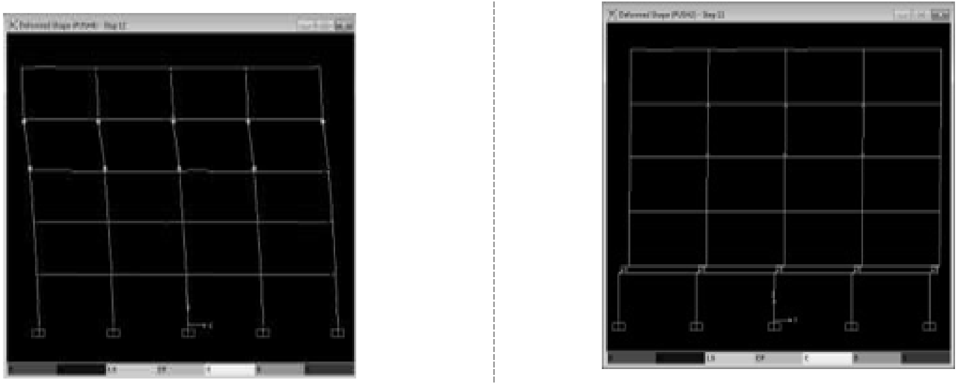
Static Nonlinear Case: Pushover (mode1)-2
Plot Type: Resultant Base Shear vs Monitored Displacement
Units: KN, m, C
Current Plot Parameters: VDPO1

Static Nonlinear Case: Pushover (mode1)
Plot Type: FEMA 440 Equivalent Linearization
Units: KN, m, C
Current Plot Parameters: F440POEL1
Performance Point (V, D): (4675.339 , -0.061)
Performance Point (Sa, Sd): (0.369 , 0.057)
Performance Point (Tsec, Ductility): (0.785 , 1.749)
Performance Point (Beff, M): (0.073 , 0.801)

Figure 22. pushover curve

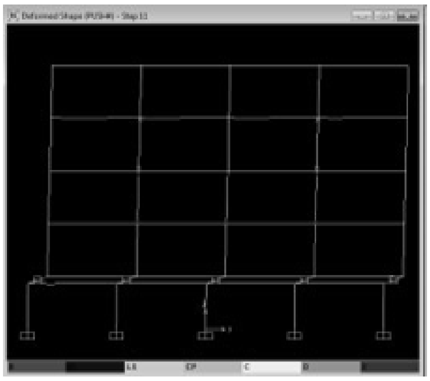
Table 5. Different scenarios for pushover analysis

Scenario	Description
Push 1	Gravity load SNPA
Push 2	Lateral loading linear distribution based on seismic codes
Push 3	Lateral loading uniform distribution
Push 4	Lateral loading distribution based on 1st mode of vibration

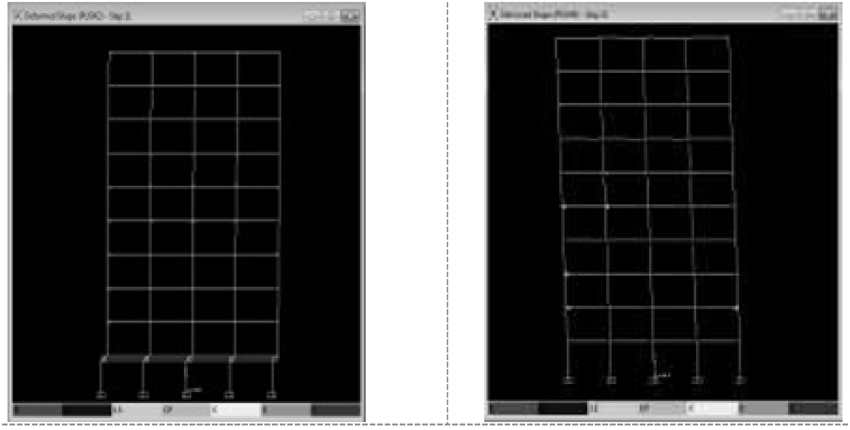


a. Final step-Push 4, 5 stories Bld.

b. Final step-Push 3, LRB – BISs, 5 stories Bld.



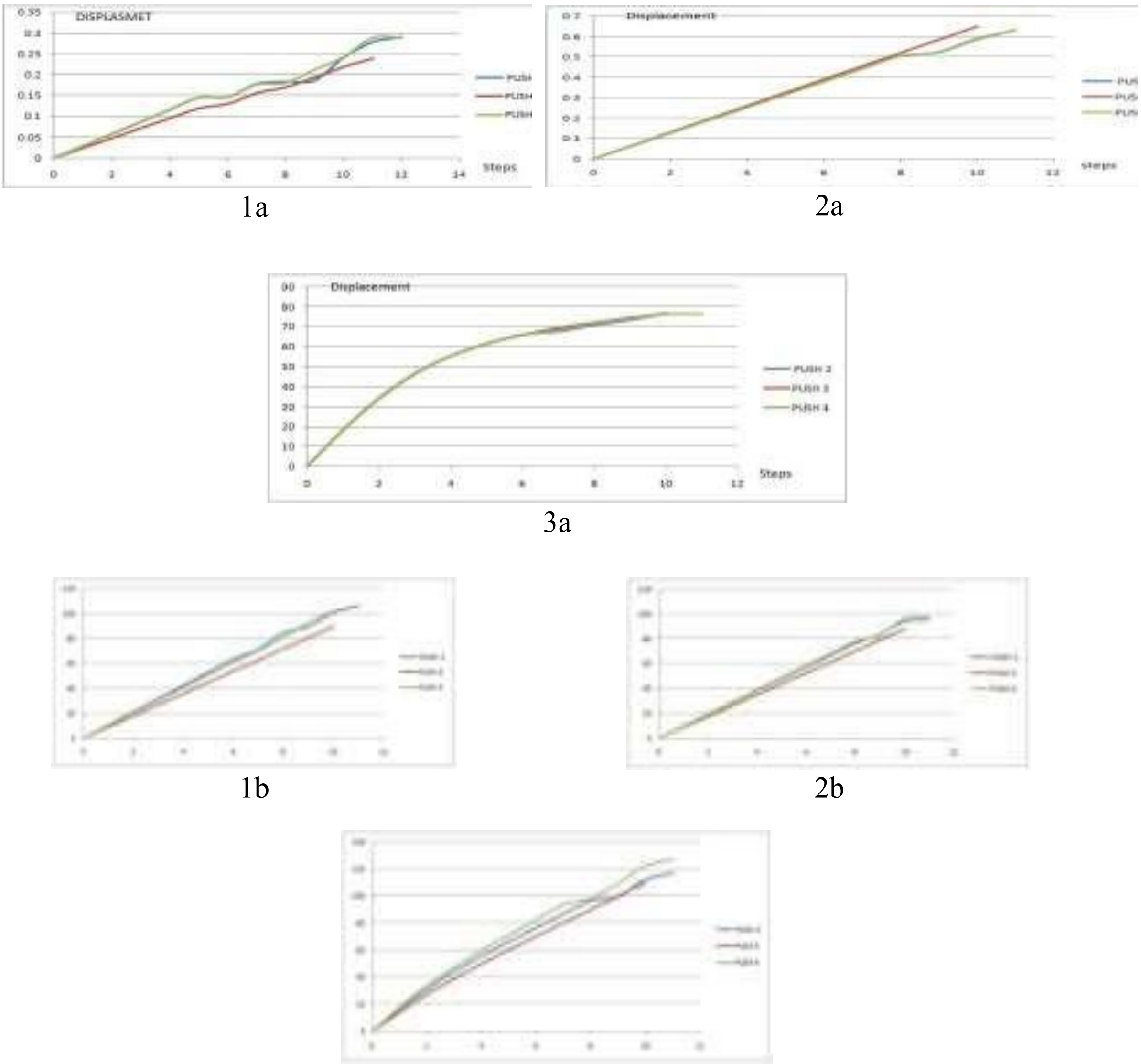
c. Final step-Push 3,HDRB –BISs, 5 stories Bld.



d. Final Step-Push 3, fix and BISs, 10th stories

Figure 23. a-d: SNPA scenario for investigated frame.

Results for the displacement of all scenarios show confidence for the structural design of frames based on codes for static design for further nonlinear anal- ysis as the target of this research (Fig. 24).



1a 2a

3a

1b 2b

3b

Figure 24: Displacement of frames for different scenarios of pushover analysis, “a” for 5 & “b” for 10 stories, and “1=Fix, 2=LRB and 3= HDRB”

7.3 Nonlinear Time History Analysis

Nonlinear time history analysis has been conducted for the 3 different assumed earthquake records and for the different condition of FEMA de-scription for performance has been used as the index for comparison. Each earthquake record was cali- brated for the important thresholds.

The first threshold as the termination point for calculation is the seismic acceleration which causes CP condition. Second threshold for termination of calculation is the acceleration equal to g (=9.81m/sec^2). All other conditions between these 2 thresholds have been investigated to find the performance of the two types of BISs.

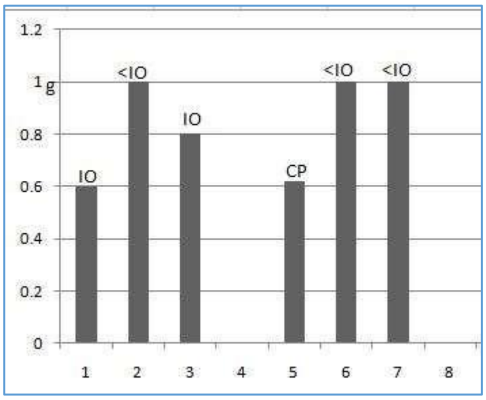
The acceleration have been increased from 0.35g and terminated on 1g.

In fact the use of 3 different records is for simulating different frequency content and possibility of occur- rence of different modes.

Termination of iterations for all models was based on the thresholds achieving in one of the analysis sort for specific record. For example for the fixed base model with 5 stories, the Cape Mendocino records show the IO condition at 0.6g however, CP condition for the El Centro earthquake. So, the ana- lyses were terminated and investigation was not conducted beyond this level for the mentioned record. Different frequency content of the assumed earthquakes shows a good interpretation of structural behavior. The results of analysis for summarized in the figure 21, 22 and 23 for different records.

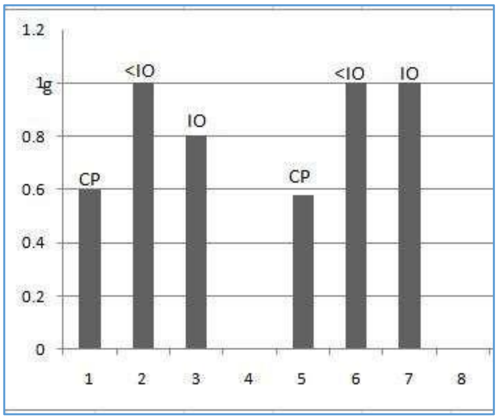
7.4 Effect of BISs on weight of structural elements

As an important index for the engineers, that en- gaged with design affairs are about the difference between BISs systems. For the iterative SNPA the minimum weight of structural elements were de- signed. The weight of structure in different models shows that HDRB will be more efficient than LRB. For the low-rise buildings exceptionally economic and for mid-rise the results are approximately the same (Fig 25).



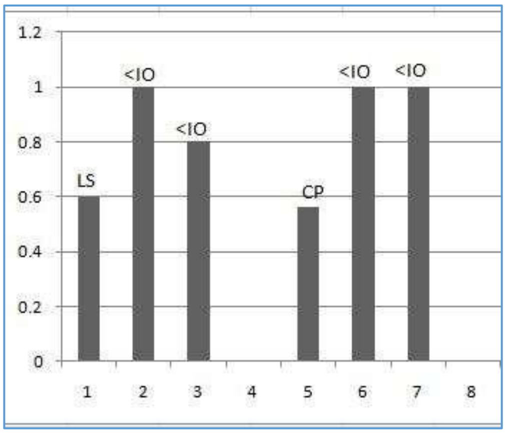
Fix LRB HDRB Fix LRB HDRB
5 Stories *10 Stories*

Figure 25: Seismic Performance of Cape Mendocino Earthquake



Fix LRB HDRB Fix LRB HDRB
5 Stories 10 Stories

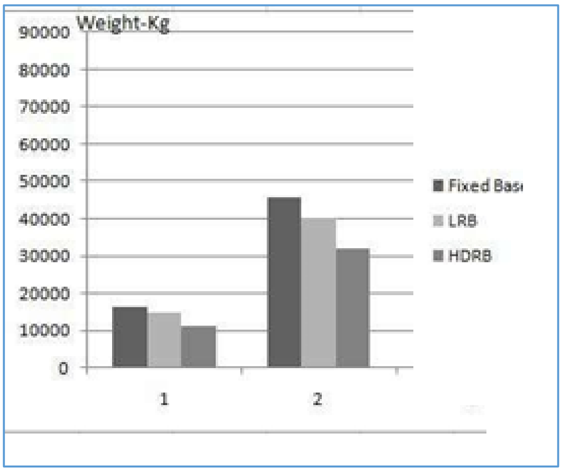
Figure 26: Seismic Performance of El Centro Earthquake



Fix LRB HDRB Fix LRB HDRB
5 Stories 10 Stories

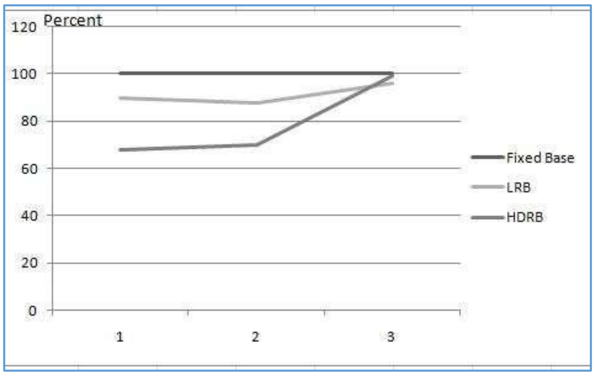
Figure 27 Seismic Performance of Northridge Earthquake

The deducted percentage of weight for the low-rise building significantly shows the efficiency of HDRB but for both LRB and HDRB the deducted weight for mid-rise model are less than five percent and their performance are the same (Fig. 27).



5 Stories 10 Stories

Figure 28 Weight of sample structures in different models



1=5 Stories 2=10 Stories

Figure 29 Deducted Percent for the weight of structure in com- pare with fixed base as the index (100%)

8. CONCLUSION

Comprehensive performance analyses of LRB and HDRB BISs has been investigated. Within the range of the parametric study of this paper, three recent examples of application of seismic isolation to build- ing frames for the 5 and 10 stories as a sample of low rise and mid rise buildings were investigated. The results show:

LRB shows a good Performance in all low rise and midrise cases.

HDRB for the midrise buildings shows better performance in compare with low rise frame.

Although the HDRB has less performance for low rise buildings for different earthquake records, the peak ground acceleration for its performance is equal to 0.8g and based on seismicity in most countries such as Iran, Pa- kistan, USA and Europe it would have enough confidence.

HDRB significantly deduct the weight of structures in compare with LRB and it is very economic.

General survey on both performance and de- duction of weight shows that HDRB is more efficient than LRB.

Deduction of weight in mid rise frame in compare with fixed base building is not sig-nificant and both systems are not economic for these frames.

The obligations for practical isolation system to be incorporated in building structures are flexibility, Damping and resistance to service loads. Additional requirements such as durability, cost, ease of installation and specific project requirements influences device selection but all practical systems should contain these essential elements.

The entire superstructure is to be supported on discrete isolators whose dynamic characteristics are chosen to uncouple the ground motion. Displacement and yielding are concentrated at the level of the isolation devices, and the superstructure behaves very much like a rigid body. A through revise has been done performed in this research regarding the sequential development of seismic isolation systems.

This study also addressed the detail cram on isolation system, properties, characteristics of various device categories, recognition along with its effect on building structures. Meticulous schoolwork has also been accomplished about installation technique for various site stipulation at low to medium seismic region.

Rigorous reckonings illustrated the isolation system as very innovative and suitable in buildings to withstand the seismic lateral forces and also are contributed sa The study concludes that while conventional reinforced concrete designs focus on preventing collapse through "ductility" (controlled damage), seismic isolation ensures **Structural Integrity** and **Post-earthquake Operability**. The practical evidence from Northridge and Kobe proves that isolated buildings protect not only the life of occupants but also the expensive internal equipment and non-structural components, making it the most reliable solution for hospitals and emergency centers.

8.1 Results and Technical Findings of Seismic Isolation Research

The research concludes that seismic base isolation is one of the most effective modern techniques for protecting reinforced concrete buildings by decoupling the structure from ground motion. The study highlights the following key results and fundamental concepts:

- **Reduction in Seismic Response**: Experimental tests at the Earthquake Engineering Research Center (EERC) demonstrated that isolation bearings could reduce structural acceleration by factors of as much as **ten** compared to conventional designs.
- **Fundamental Design Equation**: The core philosophy of base isolation shifts from increasing capacity to reducing demand, governed by the basic safety requirement: **CAPACITY > DEMAND**.

- **Period Elongation**: By interposing a layer with low horizontal stiffness, the building's fundamental frequency becomes much lower than its fixed-base frequency, shifting the structure to a region of lower acceleration in the response spectrum.
- **Mechanical Behavior of Isolators (LRB and HDRB)**:
  - **Lead Rubber Bearings (LRB)**: Provide an elastic restoring force and high damping through the hysteretic energy dissipation of the lead plug.
  - **High Damping Rubber Bearings (HDRB)**: These exhibit nonlinear stiffness where shear stiffness is high for small strains (wind loads) but decreases by a factor of 4 or 5 as strain increases, providing a "fail-safe" mechanism at strains greater than 100%.
- **Energy Dissipation**: The system restricts the amplitude of motion through damping elements, where the energy dissipated is represented by the area enclosed in the **idealized force-displacement (Hysteresis) loop**.
- **Operational Integrity**: Unlike conventional design which focuses on preventing collapse through ductility (permanent damage), seismic isolation ensures the safety of internal contents and post-earthquake operability, making it ideal for critical facilities like hospitals

8.2 Quantitative Performance and Case Studies of Seismic Isolation Systems

The effectiveness of seismic isolation is best demonstrated through a comparison between ground motion and the actual structural response. Based on recorded data from major seismic events and experimental tests at the Earthquake Engineering Research Center (EERC), the following table summarizes the significant reduction in peak accelerations show the : Comparative Seismic Response in table 6.

Table 6: Comparative Seismic Response (Fixed-Base vs. Isolated-Base)

Case Study / Location	Earthquake Event (Year)	Peak Ground Acceleration (PGA)	Isolated Structure Acceleration	Reduction Factor
USC Teaching Hospital (USA)	Northridge (1994)	0.49g	0.10g - 0.13g	~ 4.0x
West Japan Postal Center	Kobe (1995)	0.41g	0.13g	~ 3.1x
EERC Laboratory Tests	Simulated	Variable	N/A	Up to 10.0x
Critical Facility (Standard)	High Seismic Zone	100% Demand	< 30% Demand	> 3.0x

1- **Key Analytical Observations for Publication:**

- **Seismic Demand Reduction:** As shown in Table 1, the isolation system successfully decoupled the structures from the ground, reducing the force felt by the building by over **70%** in real-world scenarios.
- **Stiffness Non-linearity:** The research identifies that for High-Damping Rubber Bearings (HDRB), the shear stiffness is significantly strain-dependent. It starts high to resist wind, decreases by **400-500%** during seismic displacement to allow isolation, and increases again at strains **>100%** as a built-in safety limit.
- **Design Philosophy:** The shift from a "ductility-based" approach (which accepts structural damage) to an "isolation-based" approach ensures that the capacity of the building remains significantly higher than the reduced demand (**Capacity > Demand**), preserving not just the life-safety but the **functionality** of the building.

2- **Governing Equations and Mechanical Behavior**

The technical efficiency of the system is derived from the following physical principles:

- **Design Philosophy:** The system shifts the structural requirement from high-strength resistance to demand reduction, expressed by:

{Capacity} > {Demand}

- **Period Elongation:** By introducing low horizontal stiffness (Kh), the natural period (T) of the building is increased according to:

$$2\pi\sqrt{\frac{m}{Kh}}$$

- This shift moves the building into a lower acceleration zone on the Seismic Response Spectrum.

3- **Damping and Energy Dissipation:** The energy dissipated per cycle (Wd) is proportional to the area of the hysteresis loop of the isolator:

$$Wd = \int f\,dx$$

8.3 DISCUSSION OF THE RESULTS

- Seismic base isolation significantly reduces the transmission of forces and accelerations from the foundation to the superstructure.
- Elastomeric, lead-rubber (LRB), and high-damping rubber bearings (HDRB) demonstrate high efficiency and stability under cyclic and dynamic seismic loading.
- Isolated structures act almost as rigid bodies, with deformations concentrated at the isolation layer, resulting in minimal inter-story drift.
- Base isolation systems increase the fundamental vibration period, reducing seismic demand and base shear forces.
- Seismic isolation offers economic advantages by reducing repair costs and ensuring operational continuity of essential facilities after earthquakes.

8.4 Recommendations

- Adopt seismic isolation systems in essential and critical structures to ensure post-earthquake functionality.
- Select the appropriate isolator type (LRB or HDRB) based on structural characteristics and seismic hazard levels.
- Conduct detailed dynamic and laboratory testing to verify isolator properties before implementation.
- Incorporate supplemental damping devices when necessary to control displacement demands.
- Update local design codes to support and regulate the use of seismic isolation technologies.
- Provide specialized training programs for engineers and designers on seismic isolation m

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Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.