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Base Isolation Systems in Multi-Storey Structures

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Abstract

Base isolation (BI) systems have been found to be effective tools to safeguard multi-storey buildings and other structures from severe earthquake excitations. It requires the structure to be separated from the ground by isolation devices which can dissipate energy. This is proven technology which may add a little to the initial cost of the building, but will prove to be less expensive in the long term. Base isolation technology introduces flexibility into the connection between the structure and the foundation. In addition to allowing movement, the isolators are often designed to absorb energy and thus add damping to the system. Furthermore reduces the seismic response of the building and also enables a building or non-building structure (such as a bridge) to survive a potentially devastating seismic impact, following a proper initial design. This study discusses the concept of base isolation and reviews existing base isolation systems

Keywords: Base isolation systems, Multi-storey buildings, Earthquake excitations, Mitigation, seismic risk, Three degrees of freedom.

1. INTRODUCTION

Structures respond to earthquake ground shaking in different ways. When the forces on a building or the displacement of the building exceeds certain limits, damage is incurred in different forms and to different extents. If a brittle building is designed to respond elastically with no ductility, it may fail when the ground motion induces a force that is more severe than the building strength. On the other hand, if the building is designed with ductility, it will be damaged but will still be able to weather severe ground shaking without failure. Since the motion of earthquakes is vibrational in nature, the principle of vibration isolation can be utilised to protect a building (i.e., it is decoupled from the horizontal components of the earthquake ground motion by mounting isolation between the building and its foundation). Such a system not only provides protection to the building but also to its contents and occupants. Base isolation is a passive structural control technique where a collection of structural elements is used to substantially decouple a building from its foundations resting on shaking ground, thus protecting the building's structural integrity. For several decades, engineers have focused on ways of designing structures that are capable of withstanding earthquake effects. This was achieved by using diagonal bracing and installation of shear walls. Flexible buildings on the other hand use isolators and dampers to minimize the level of excitation (Morgan (2007)). Rigid techniques are preferred to flexible techniques because they are more mature. However, in the case of large-scale earthquake events, considerable inter-storey floor accelerations and drift of highly stiff buildings raises risks of brutal devastations.

2. CONCEPT OF BASE ISOLATION

Seismic action generates ground displacements, which are then transferred to the supports of the structure. As a result, the structure experiences deformations and accelerations, often larger than the one of the ground. Among the structural mitigating technologies available to earthquake is the base isolation technique. Base isolation decouples the structure vibration from the ground vibration, preventing most of the horizontal movement of the ground from being transmitted to the buildings (Figure 1). The base isolation technique is based on the principle that during earthquakes, the vibration natural period is shifted from a short time range to long time range, which effectively reduces the damaging effects. The most important feature of this technique is that it introduces elasticity into the connection between the foundation and the structure itself. Only a few devices can reduce both horizontal and vertical responses of structures at the same time (Lu & Lin (2008)).

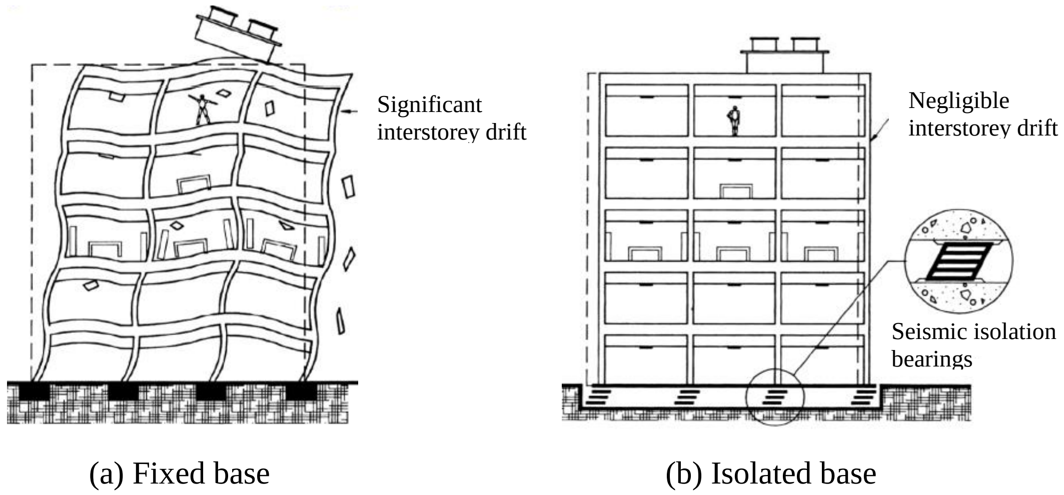


Figure 1. Fixed base and isolated base (Lu & Lin (2008))

In a structure with fixed base, lateral deformations are distributed along the building height Multi Degree of Freedom (MDOF) system, whilst in a base-isolated structure lateral deformations are concentrated in the isolation devices, the structure behaving essentially as a SDOF system. Seismic isolation is achieved by inserting devices between the foundation and structure that has small lateral stiffness (increases period), large vertical stiffness and large damping. A base-isolated structure has a substantially larger period of vibration than a structure with fixed base (Figure 2 (a)). The effect of increasing the period is to reduce accelerations (and related forces) and increase displacements. To reduce displacements, it is important that the isolating device can offer significant damping (Figure 2 (b)).

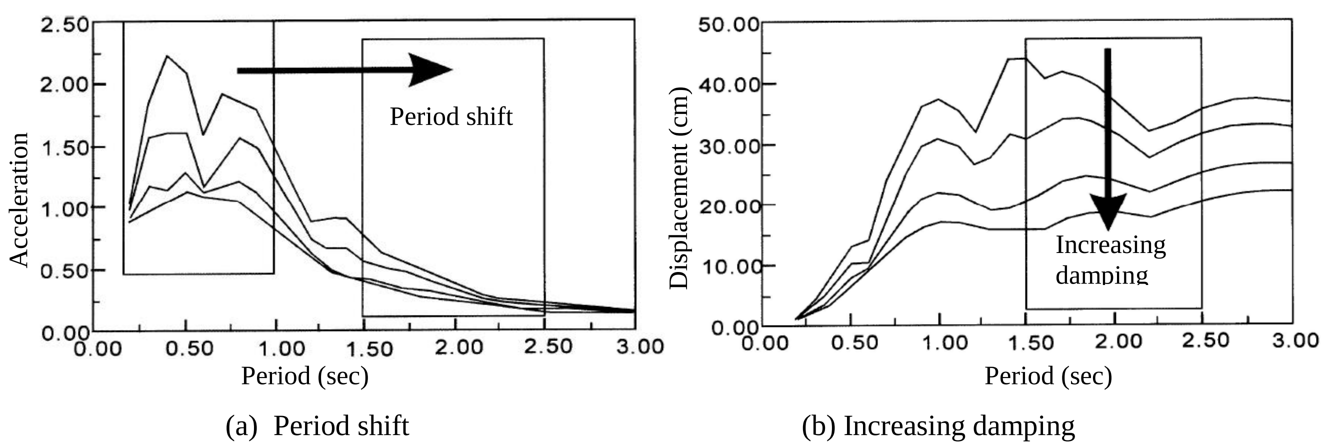


Figure 2. Principles of seismic isolation

Base isolation is efficient in rigid structures (low-rise and medium-rise buildings), with periods of vibration below 1 sec. Using isolator devices, the period can be increased to 1.5-2.5 seconds, which is an important reduction of seismic forces induced in the structure. High-rise buildings have large period of vibration, their design being often governed by wind loading. Base isolation is efficient for structures with a low ratio between the height and largest dimension of the building. Overturning leads to difficulties in operation and design of isolators in high-rise structures.

3. A BRIEF HISTORY OF BASE ISOLATION SYSTEMS

Although the first patents for base isolation were in the 1800's, and examples of base isolation were claimed during the early 1900's (e.g. Tokyo Imperial Hotel) it was the 1970's before base isolation moved into the mainstream of structural engineering. Isolation was used on bridges from the early 1970's and buildings from the late 1970's. Bridges are a more natural candidate for isolation than buildings because they are often built with bearings separating the superstructure from the substructure. The first bridge applications added energy dissipation to the flexibility already there. The lead rubber bearing (LRB) was invented in the 1970's and this allowed the flexibility and damping to be included in a single unit. About the same time the first applications using rubber bearings for isolation were constructed. However, these had the drawback of little inherent damping and were not rigid enough to resist service loads such as wind.

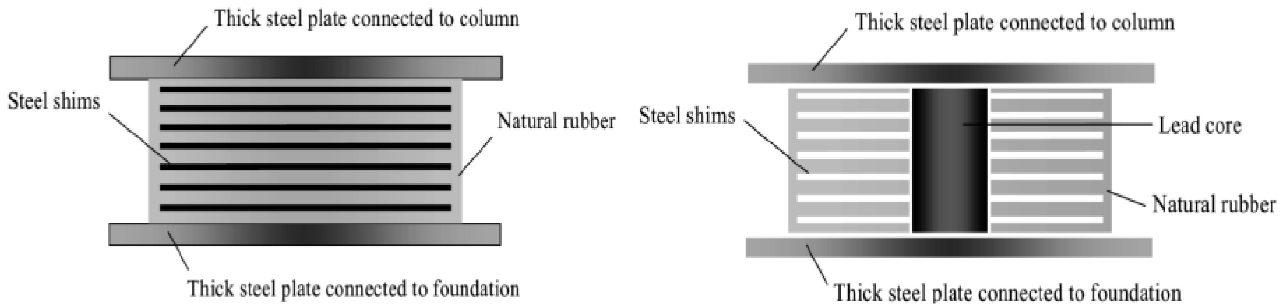
In the early 1980's developments in rubber technology lead to new rubber compounds which were termed "high damping rubber" (HDR). These compounds produced bearings that had a high stiffness at low shear strains but a reduced stiffness at higher strain levels. On unloading, these bearings formed a hysteresis loop that had a significant amount of damping. The first building and bridge applications in the U.S. in the early 1980's used either LRBs or HDR bearings.The development of the friction pendulum system (FPS) shaped the sliding bearing into a spherical surface, overcoming this major disadvantage of sliding bearings. As the bearing moved laterally it was lifted vertically. This provided a restoring force. Although many other systems have been promulgated, based on rollers, cables etc., the market for base isolation now is mainly distributed among variations of LRBs, HDR bearings, flat sliding bearings and FPS.

3.1. Elastomeric Bearings

The base isolation system that has been adopted most widely in recent years is typified by the use of elastomeric bearings, where the elastomer is made of either natural rubber or neoprene. In this approach, 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. Elastomeric bearing comprises of bonded alternating rubber and steel layers, as shown in Fig 3 (a), and is most common base isolation system to date. The steel layer keeps the rubber layer from bulging laterally and provides the rigidity so that the bearings can support high vertical loads in bridges and buildings, whilst the rubber layer, which is made out of either natural rubber or synthetic rubber (such as neoprene) provides the required flexibility when subjected to horizontal loads. Elastomeric bearing allow the super-structure to move significantly during earthquake motions without facing any form of disfigurement. Since elastomeric bearings experience consistent expansion and contraction they may require constant replacement. The pads used for the elastomeric bearings are made of laminated steel. Elastomeric bearing can be damaged through tearing of rubber under severe earthquake. The bearing force generated by lead rubber bearing can be represented by Equation 1.

$$F_b = C_b \dot{U}_b + \alpha_b K_b U_b + F_z \tag{1}$$

where, C_b is the damping coefficient , $\dot{U}_b$ is the velocity, α_b is computed by the following expression $\alpha_b = \alpha_b^2 m_t q / f_y$, f_y is yield strength of the isolator, K_b is the stiffness, U_b is the displacement, $F_z = (1-\alpha_b) f_y q z_b$ is the restoring force as a result of presence of lead core , α_b is computed by the following expression $\alpha_b = \alpha_b^2 m_t q / f_y$, f_y is yield strength of the isolator, m_t is the mass of the superstructure, q is characteristics strength of the lead core and z_b is the non-dimensional hysteretic displacement component. Due to low critical damping (typically 2%-3%), elastomeric bearings have little resistance to service load, and additional damping devices are required in order to control higher lateral displacement. Elastomeric bearings has a relatively low manufacturing cost compared to other types of bearings, their mechanical properties are independent of temperature and aging and do not exhibit creep under long-term loading.



(a) Elastomeric bearing (b) Lead-rubber bearing

Figure 3. Elastomeric and lead-rubber bearing

3.2. Lead-rubber bearings

Lead-plug bearings are fabricated by plugging a lead core into the elastomeric bearing. The solid plug in the middle absorbs energy and adds decamping (Jung, Eem, Jang, & Koo (2011)), while natural rubber is useful in facilitating flexibility through its ability to move and return to its normal position. The performance of the lead-plug bearing depends on the imposed lateral force. If the lateral force is small, the movement of the steel shims is restrained by the lead core, and the bearing displays higher lateral stiffness. As the lateral force becomes larger, the steel shims force the lead core to deform or yield, and the hysteretic damping is developed with energy absorbed by the lead core. The equivalent damping of the lead-plug bearing varies from 15% to 35%.

3.3. Sliding systems

A sliding system is a combination of levers that allow two adjacent solids slide past each other or on each other with minimum friction (Usman et al (2009)). This system is based on the hypothesis that the lower the friction coefficient, the less the shear transmitted [2]. The horizontal frictional force offers resistance to motion and dissipates energy. For sliding to occur the intensity of exciting force must be more than frictional force of isolator. The technology of sliding systems was applied in the United States of America at the start of the 20th century. Many wooden structures in America are developed with a three-layered base that comprises the foundation (concrete), a sliding steel system, and a floor on top of it. The sandwiched steel base allows the house to sway from side to side during relatively strong quakes and indeed holds the structure intact [28]. The movement involves little inertia with minimal implications for occupants (house) and users (bridge), and thus is often unnoticed. Sliding systems are also used in bridges to allow the bridge withstand strong winds and tremors, however, it is not easy to apply these systems in structures that carry a lot of weight. If effectively applied, the swinging or sliding of the structure effectively minimizes the susceptibility of a structure to shear and thrust forces (Usman et al (2009)). Due to the fact that they tend to shake earlier than most of the structures under a quake, they are effective base-isolation systems. Sliding systems are nonetheless dangerous where the structure is old (over 5 decades) as it may have loose bolts that may give way in the wake of tremors.

3.4. Friction Pendulum

A similar system is the Friction Pendulum Bearing (FPB), another name of Friction Pendulum System (FPS). It is based on three aspects: an articulated friction slider, a spherical concave sliding surface, and an enclosing cylinder for lateral displacement restraint (Zayas, 1990). The bearing material of the friction pendulum is provided in between the base and the slider, and it is hardly used separately from sliding systems and elastomeric bearings. The principle of the friction pendulum is that during an earthquake, the slider slides over a concave surface so as to provide the isolation. To facilitate easy sliding, the spherical surface is normally coated with Teflon of approximately 3% friction coefficient. At the end of earthquake, the slider moves back to its original position under action of gravitational force, due to concavity of the base, thereby restoring the structure at its original position and minimizing residual displacement. During an earthquake, the slider moves on the spherical surface lifting the structure and dissipating energy by friction between the spherical surface and the slider. Increasing the sliding period reduces the base shear and increases the displacement, and decreasing the friction coefficient reduces the base shear and increases the displacement. Thus the friction coefficient should be such that it should provide enough rigidity as well as the isolation by shifting the effective period from the duration of pulses. The main limitation of this system is that it is designed for a specific level (intensity) of ground excitation, since the spherical surface has a constant time period, which solely depends upon the radius of curvature. In addition, if the excitation period and isolator period coincides then the friction pendulum system faces the problem of resonance (Weisman & Warn (2012)).

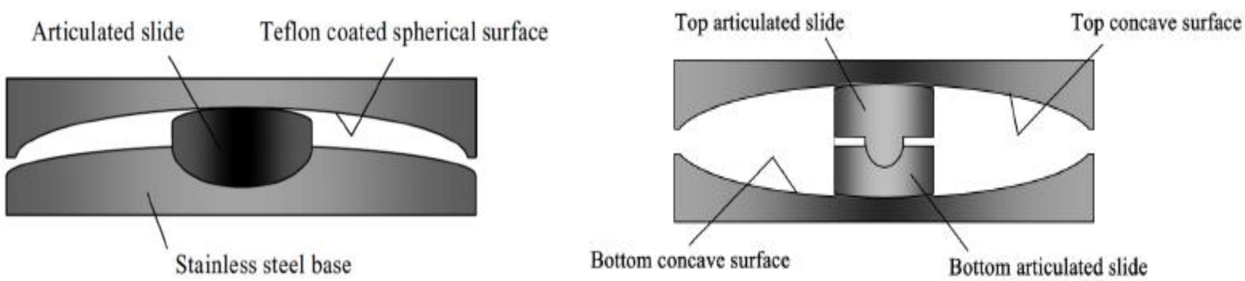


Figure 4. Friction pendulums

Pendulum systems (friction pendulums) are difficult to construct and quite expensive to maintain. The measurements concerning the particular angles of tilt, the pulley structures as well as the general design of the material such as weight specifications and the handling of the CoG (Centre of Gravity) makes it among the most expensive base isolation structures[43]. Figure 2.2 presents an illustration of the friction pendulum concept that is utilized in base isolation of buildings

3.5. Pot Bearings

Pot bearings have been applied mostly in bridges to restrict both vertical and horizontally induced motion. These bearings can accommodate very high loads of up to over 45 000 kN. In a pot bearing an encased natural rubber pad is placed in a steel pot under high pressure which makes the pad work like a liquid. The flexibility of the rubber facilitates tilting of the piston along the horizontal axis (Rabiei & Khoshnoudian (2011)). The entire structure of the pot bearing is detachable since parts require occasional repair and replacement.

4. CONCLUSION

This paper discusses the concept of base isolation and reviews existing base isolation systems. Most of the base isolation systems reviewed can absorb earthquake energy in 2 dimensions. In conclusion, the friction pendulum is observed to be the only base isolation that is capable is absorbing earthquake energy in both three principal directions. The observed research results , it shows that the structural deformations going into the inelastic/plastic range and the consequent is likely to be completely eliminated in FPS, and the structure needed to to designed for much smaller acceleration. In addition, the relative sotrey displacement (drifts) tend to be reduced hence less damage to walls, cladding etc is minimized or eliminated. Also the response acceleration at higher floors tends to be reduced much hence the damage are minimized. Investigation on this aspect are still on-going, as 3-dimensional systems are new technologies for absorbing earthquake energy.

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