International Journal of Scientific & Engineering Research, Volume 5, Issue 5, May-2014
ISSN 2229-5518

State Of Art Review-Base Isolation for Structures

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Abstract— Base isolation is a system that decouples the superstructure from substructure by reducing the horizontal components of ground motions. It is achieved by interposing structural elements like elastomeric rubber bearings or friction pendulum bearings between the structure and the foundation. The mechanism of the base isolation increases the natural period of the overall structure and decreases its acceleration response. Both the floor accelerations and the interstory drift are considerably and simultaneously reduced. The earthquake forces do not get directly transferred to the super structure as in case of Fixed Base structures. This technique has been incorporated for the retrofitting of the existing structures and monuments and also for the newly constructed low to medium rise buildings. In this paper, an attempt is made to present an overview of concept and dynamics of base isolation. The different types of isolators are also briefly explained. The various applications of base isolation used in different parts of the world are highlighted in this paper. Further, latest developments in this field are also mentioned.

Index Terms— Base Isolation, Period Shift Effect, Elastomeric Rubber Bearings, Friction Pendulum, Retrofitting, Lead Plug.

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1 Introduction

Base isolation, also known as seismic base isolation, is a seismic mitigation approach in which the building is protected from the horizontal components of earthquake forces. To protect a building from the damaging effects of earthquake, specially designed isolators with low horizontal stiffness are introduced above foundation. One of the main advantages of seismic isolation includes the ability to eliminate or significantly reduce structural and nonstructural damage in a building, and also to enhance the safety of the building contents and architectural facades, and to reduce seismic design forces. These potential benefits are greatest for stiff structures fixed rigidly to the ground, such as low- and medium-rise buildings, nuclear power plants, bridges, and many types of equipments. Some tectonic and soil-foundation conditions may, however, preclude the use of seismic isolation.

2. Concept and Dynamics

2.1 Fundamentals of isolation

The fundamental principle of base isolation is to modify the response of the building so that the ground can move below the building without transmitting these motions into the building[1]. The building must behave like a rigid body such that all the points in the building move in the same direction and by same amount as the ground. This method of base isolation works by interposing structural elements with low horizontal stiffness between the structure and the foundation. This gives a fundamental frequency that is much less than both its fixed base frequency and 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 be rigid. The higher modes that are orthogonal to the first mode, do not participate the motion and thus ground motion cannot be transmitted into the structure[3]. The natural period of the fixed-base structure undergo a jump and the new base-isolation structure has a new natural period. This further reduces acceleration and base shear in superstructure. The flexibility of isolators between structure and its foundation lead to a bigger fundamental period for structural. This is known as Period shift effect, as shown in Fig 1. Hence, base isolation is suitable for low to medium rise building as their fundamental natural period without isolation is in lower range with maximum acceleration response.

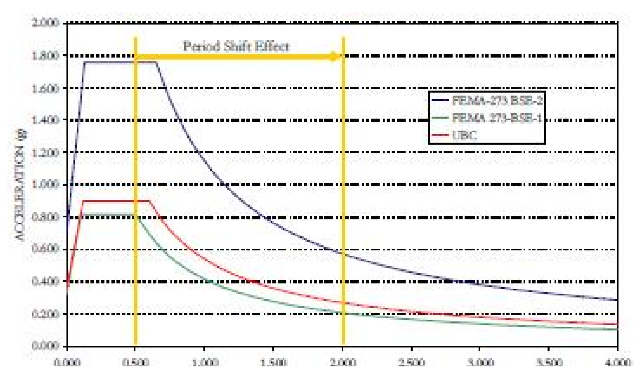

Fig. 1 Period Shift Effect

2.2 Dynamic response of a base isolated structure [2]

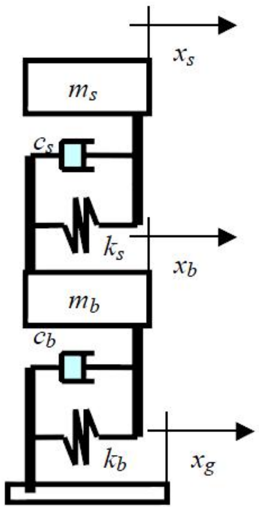

Fig 2.2[2]

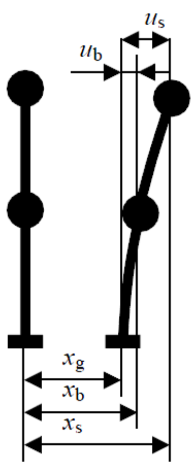

Fig 2.3[3]

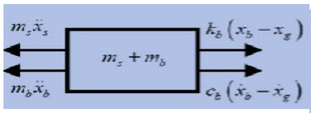

Fig.2.4[2]

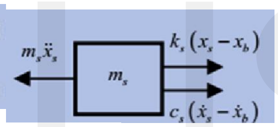

Fig. 2.5 [2]

Let a structure isolated (Fig. 2.2, 2.3) from this base by a certain isolation system. Due to large differences between mechanical characteristics of the structural materials and isolator materials two degree of freedom simplified model can be used to predict the dynamic response of such a base isolated structure. The superstructure is assimilated to single degree of freedom system (characterized by its generalized mass m_s , its generalized damping c_s, and its generalized stiffness k_s) mounted on the base assimilated to another SODF system, characterized by its generalized mass m_b , its generalized damping c_b , and its generalized stiffness k_b. If x_g, x_b, x_s are ground, base and superstructure absolute displacements, the base and superstructure displacements relative to the ground is

$$u_b = x_b - x_g \quad ; \quad u_s = x_s - x_g \tag{2.1}$$

To In order to determine the motion equations one can disconnect the two masses as in Fig. 2.4, 2.5 and thus:

3. TYPES OF ISOLATORS

Most of the base isolation system includes either the elastomeric bearings or the sliding bearings with the sliding surfaces. Nowadays there are systems that combine both the bearings. Some of isolation devices which are in use are discussed briefly here.

$$\begin{cases} m_b\ddot{x}_b + m_s\ddot{x}_s + c_b(\dot{x}_b - \dot{x}_g) + k_b(x_b - x_g) = 0 \\ m_s\ddot{x}_s + c_s(\dot{x}_s - \dot{x}_b) + k_s(x_s - x_b) = 0 \end{cases} \tag{2.2}$$

Because:

$$x_b = u_b + x_g \quad ; \quad x_s = u_s + u_b + x_g \tag{2.3}$$

the system (2.2) become:

$$\begin{cases} m_b\ddot{u}_b + m_s(\ddot{u}_s + \ddot{u}_b) + c_b\dot{u}_b + k_b u_b = -(m_b + m_s)\ddot{x}_g \\ m_s(\ddot{u}_s + \ddot{u}_b) + c_s\dot{u}_s + k_s u_s = -m_s\ddot{x}_g \end{cases} \tag{2.4}$$

or, in matricial form:

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = -\mathbf{M}\delta\ddot{x}_g \tag{2.5}$$

where the mass, damping and stiffness matrices are, respectively:

$$\mathbf{M} = \begin{bmatrix} m_t & m_s \\ m_s & m_s \end{bmatrix} \; ; \; \mathbf{C} = \begin{bmatrix} c_b & 0 \\ 0 & c_s \end{bmatrix} \; ; \; \mathbf{K} = \begin{bmatrix} k_b & 0 \\ 0 & k_s \end{bmatrix} \tag{2.6}$$

m_t being the total mass: $m_t = m_b + m_s$ and δ a position vector: $\delta = \{1 \quad 0\}^T$.

3.1Elastoeric bearings

An elastomeric bearing consists of alternating layers of rubber and steel shims bonded together as shown in Fig 3. The steel shims perform the function of preventing the rubber layers from bulging and hence these bearings can support high vertical loads. These are much more flexible under lateral loads than vertical loads. Elastomeric bearings use either natural rubber or synthetic rubber (such as neoprene), which have little inherent damping, usually 2% to 3% of critical viscous damping. These are further of two types: low damping type and high damping type. This type of isolation device has been used in Foothill Community Law and Justice Center, Rancho Cucamonga, CA.

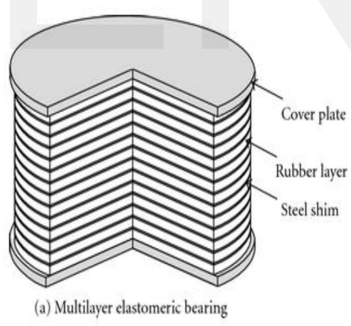

Fig. 3 Elastomeric Bearings [4]

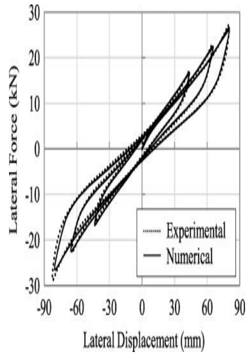

Fig.4 Hystereti loop [5]

3.1 High damping rubber (HDR) bearings

The term high damping rubber bearing (Fig. 2.6) is applied to elastomeric bearings where the elastomer used (either natural or synthetic rubber) provides a significant amount of damping, usually from 8% to 15% of critical. This compares to the more "usual" rubber compounds, which provide around 2% damping. The additional damping is produced by modifying the compounding of the rubber and altering the cross link density of the molecules to provide a hysteresis curve in the rubber. Therefore, the damping provided is hysteretic in nature (displacement dependent). For most HDR compounds the viscous component of damping (velocity dependent) remains relatively small (about 2% to 5% of critical). The damping pro-

vided by the rubber hysteresis can be used in design by adopting the concept of "equivalent
As for LRBs, the effective damping is a function of strain. For most HDR used to date the effective damping is around 15% at low (25% to 50%) strains reducing to 8%-12% for strains above 100%, although some synthetic compounds can provide 15% or more damping at higher strains. The high damping rubber bearings have been installed in the retrofitting of Los Angeles City Hall, California.

3.1 Lead rubber bearings (LRB)

A lead-rubber bearing as shown in Fig. 5 is formed by using a lead plug that is fitted into a pre-formed hole in an elastomeric bearing. The lead core provides rigidity under service loads and energy dissipation under high lateral loads. The entire bearing is encased in cover rubber to provide environmental protection. When subjected to low lateral loads (such as minor earthquake, wind or traffic loads) the lead-rubber bearing is stiff both laterally and vertically. The lateral stiffness results from the high elastic stiffness of the lead plug. At higher loads, levels the lead yields and the lateral stiffness of the bearing is significantly reduced. This produces the period shift effect characteristic of base isolation. As the bearing is cycled at large displacements, such as during moderate and large earthquakes, the plastic deformation of the lead found energy as hysteretic damping. The equivalent viscous damping produced by this hysteresis is a function of displacement and usually ranges from 15% to 35%. [1] This system of lead plug has been installed in the retrofitting of Oakland City Hall California

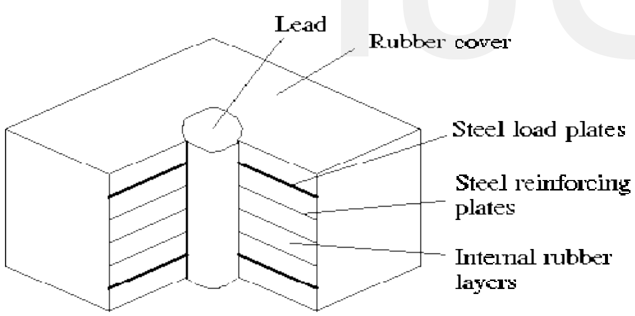

Fig. 5 Lead Rubber Bearing [6]

3.3 Flat slider bearings

Sliding bearings provide an elastic-perfectly plastic hysteresis shape with no strain hardening after the applied force exceeds the coefficient of friction times the applied vertical load. This is attractive from a structural design perspective as the total base shear on the structure is limited to the sliding force. *An ideal friction bearing provides a rectangular hysteresis loop, which provides equivalent viscous damping of 63.7% of critical damping, much higher than achieved with LRB's or HDR bearings*. In practice, sliding bearings are not used as the sole isolation component for two reasons:
(i) Displacements are unconstrained because of the lack of any centering force. The response will tend to have a bias in one direction and a structure on a sliding system would continue to move in the same direction as earthquake aftershocks occur.
(ii) A friction bearing will be likely to require a larger force to initiate sliding than the force required to maintain sliding. This is termed static friction. If the sliders are the only component then this initial static friction at zero displacement will produce the governing design force [1]

3.4 Friction Pendulum System

It is a type of frictional isolation system (Fig. 6) that combines a sliding action and a restoring force. It consists of an articulated slider that has the tendency to move on a spherical surface. Both the sides of this slider are coated with a low friction composite material. Now, as the slider moves over the spherical surface, it causes the supported mass to rise and hence provides the restoring force for the system. Friction between the slider and the spherical surface produces damping in the isolators [3]. Live example using this system is U.S. Court of Appeals, San Francisco, CA and San Francisco International Airport, International Terminal, California.

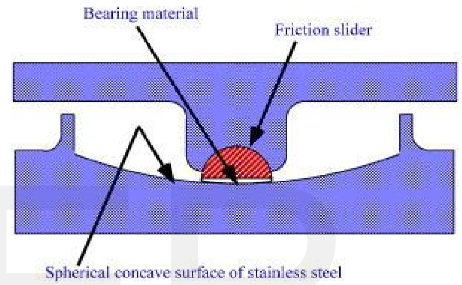

Fig. 6: Friction Pendulum [7]

3.5 Ball and roller bearings

A ball system is under development using a compressible material, which deforms as it rolls providing some resistance to service loads and energy dissipation. Ball and roller bearings constructed of steel or alloys usually have the problem of flattening of the contact surface with time when they are subjected to a high stress, as they would be under buildings and bridges. This appears to be a major disadvantage. Also, they do not provide either resistance to service loads or damping so there would be a need to use these in collaboration with other systems. As such their practical use is limited.

4. Applications of base isolation in buildings

All tableVarious structures have incorporated base isolation in order to minimize the damages caused by the earthquake forces. Base isolation will *substantially decouple a superstructure from its substructure resting on a shaking ground thus protecting a building or non-building structure's* integrity. This helps in reducing the catastrophic consequences of the earthquake ground motion. In the following buildings, base isolation is being used successfullys.

4.1 Oakland City Hall, California (retrofit)

This building (Fig. 7) was severely damaged in 1989 Loma Prieta Earthquake. Being built in 1914 was the tallest building on the west coast at the time of its construction. Its height was surpassed by the Los Angeles City Hall which was built in 1928. This uses 110 lead-plug bearings ranging from 737 mm to 940 mm in diameter. The cost of the retrofit was about $84 million with the isolators of about 2.5 % of this cost [3]

Fig. 7 Oakland City Hall

4.2 San Francisco City Hall, California (retrofit)

This building was designed in 1912 to replace the previous structure that was destroyed in the 1906 San Francisco earthquake [3].The two-block-long building was cut from its foundation and made to "float" on 530 isolators, shock absorbers designed to dissipate earthquake motion and allow the building to sway horizontally up to 26 inches without shaking apart (Fig. 8)

Fig. 8 San Fransisco City Hall, California

4.3 Los Angeles City Hall, California (retrofit)

The total floor area close to 83,000 m^2. City Hall (Fig. 9) has been placed on top of a mechanical system of 475 high damping rubber isolators, 60 sliders, and 52 mechanical viscous dampers employing base isolation technology that will dampen the violent movements of the earth during a seismic event. Also, 12 viscous dampers are installed between the twenty-fourth and twenty-sixth floors to control interstory drifts at these soft-storey levels [3]

Fig. 9Los Angeles City Hall, California

4.4 San Francisc International Airport , International Terminal, California.

The International Terminal (Fig. 10) is among the largest base-isolated structures in the world. It is supported on 267 Friction Pendulum isolators which are placed between the building and the building's foundation. The bearing is very stiff and strong in the vertical direction, but flexible in the horizontal direction. The building is designed to remain functional under almost any size earthquake.

Fig. 10 San Fransisco Airport International Terminal , Califor-

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4.5 Mackay School of Mines University of Nevada - Reno, Nevada (retrofit).

The slider and elastomer combination was used in the 1992 seismic rehabilitation of the Mackay School of Mines at the University of Nevada at Reno [3] and it uses 44 Teflon slider plates and 64 base-isolation columns in the sub-basement (Fig. 11). Mackay Mines is just the second historic building in the United States with base-isolation retrofitting.

Fig. 11 Mackay School of Mines University of Nevada

4.6**India-Bhuj Hospital**

The new 30,000m² hospital (Fig. 12) is the first building in India to be fitted with the technology. It is reputed to be able to stand a force 10 tremor on the Richter scale. It was designed after the devastating effects caused by Bhuj earthquake on 26th January 2001.

FIG.12 INDIA-BHUJ HOSPITAL

5. FEASIBILITY OF SEISMIC ISOLATION EQUATIONS

There are various factors that help in deciding the feasibility of base isolation. These are described in the following points:

5.1 The Weight of the Structure

A good isolation systems work best with heavy masses. In order to obtain effective Isolation we need to achieve a long period of response. The period is proportional to the square root of the mass and inversely proportional to the square root of the stiffness.

5.2. The Period of the Structure

The buildings that are most suitable for base isolation are those which have a short natural period, less than about 1 second, so that their time period could be lengthen and thereby, reducing its frequency. For buildings, that is usually less than 10 stories and for flexible types of structure, such as steel moment frames, probably less than 5 stories. The main purpose of any isolation systems is to provide a shift in the period to the 1.5 to 3.5 second range. But if the structure is already in this period range then base isolation would be useless n instead will lead to an extra cost.

5.3. Seismic Conditions Causing Long period waves

. Some sites have a travel path from the epicenter to the site such that the earthquake motion at the site has a long period motion. This situation most often occurs in alluvial basins and can cause resonance in the isolated period range. Isolation may make the response worse instead of better in these situations. Examples of this type of motions have been recorded in Mexico City and Budapest [1]

5.4. Subsoil Condition

Isolation works best on rock and stiff soil sites. Soft soil has a similar effect to the basin type conditions mentioned above; it will modify the earthquake waves so that there is an increase in long period motion compared to stiff sites. Soft soil does not rule out isolation in itself but the efficiency and effectiveness will be reduced [1

5.5. Near Fault Effects

One of the most controversial aspects of isolation is that the system will operate if the earthquake occurs close to the structure (within about 5 km). Close to the fault, a phenomenon termed "fling" can occur. This is characterized by a long period, high velocity pulse in the ground acceleration record. Isolation is being used in near fault locations, but the cost is usually higher and the evaluation more complex. In reality, any structure near to a fault should be evaluated for the "fling" effect and so this is not peculiar to isolation [1]

5.6. The Configuration

Base isolation requires a plane of separation. Large horizontal offsets will occur across this plane during an earthquake. The space needed to allow for these displacements (often termed the "rattle" space) may range from less than 100 mm (4 inches) in low and moderate seismic zones up to 1 meter or more (40 inches) in high seismic zones close to a fault. If there is an obstruction within this distance then isolation will not work. Impact with other structures, or retaining walls, will cause large impact accelerations that negate the use of isolation in the first place Thus, a simple and a regular building must be configured [1]

6. Scope of work

Base isolation provides protection not only to the building but also to its contents and occupants. It has been widely used in seismic retrofitting of the structures and the monuments. Base isolation technique has also been applied for the newly constructed low to medium rise buildings, heavy mass buildings, and squat buildings. This has generally been adopted in sites having hard or stiff soil condition. Although base isolation for buildings is thoroughly researched topic but now a day, research is being done in the few following areas :

(i) Hybrid base isolation has been an upcoming research area in which semi active base isolation technique is used.
(ii) As superstructure moves as a rigid body, pounding of two adjacent isolated buildings is of interest.
(iii) Extensive study is required for near faults effects on isolation system.
(iv) Isolators at locations other than above foundation.

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