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Study on a Base Isolation System

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Abstract

The research presented herein investigates the ability of an adaptive seismic isolation system to protect structures subjected to a variety of earthquake ground motions. Seismic isolation enables reduction in earthquake forces by lengthening period of vibration of the structure. An base isolation system must satisfy four basic criteria of effectiveness, in particular, acceleration response, shear and overturning moments are reduced by a factor of four to eight for buildings mounted on isolators. A particular GAPEC type of isolation system adopted in New Bhuj Hospital that collapsed during Bhuj 2001 earthquake and completed with earthquake engineering New Zealand Technology is studied.

Keywords: *GAPEC SYSTEM, Base isolation, New Bhuj Hospital, Earthquake engineering New Zealand Technology.*

1. Introduction

A new trend for earthquake – resistant structures has developed for several years, which intends to confine the seismic energy in a limited region of the structure acting as shock absorbers. Conventional seismic design is generally not acceptable for certain structures that must remain fully functional during a major earthquake (eg: hospitals, fire stations, and emergency command centers). One approach to protecting such structures involves the installation of special seismic protection systems that ensure essentially elastic behavior of the structure during a major earthquake. The mechanisms to reduce the seismic effects are roughly grouped into four types, base isolation type, energy dissipation type, soft spring type and automatic control type. GAPEC system belongs to base isolation method, which has ability of energy dissipation in case of large deflection.

A seismic isolation system may be used to decouple the structure response from the ground motion while a supplemental damping system may be used to absorb portion of the energy transferred into the structure. Alternatively, a hybrid isolation system consisting of base isolation bearing combined with supplemental dampers offers a very reliable and cost – effective approach to mitigating the effects of strong earthquake – induced ground motion. There are limitations, however, to the performance of hybrid isolation systems. In particular, such systems may not perform well for structures that are prone to wide variety of earthquake ground motions.

A new trend for earthquake – resistant building has developed in the last few years that intend to dissipate the seismic energy through structural systems installed at the base of building. These systems are intended to be perfectly elastic so that the building is restored to its original position after the seismic event. According to the laws of dynamics, such a system would increase the natural period of the building and decrease the acceleration response correspondingly. Recent tremendous progress in the rubber technology has made it possible to construct such a system with safety requirement in earthquake technology.

2. Fundamentals of Base Isolation system

A base isolation system must satisfy four basic criteria of effectiveness:

1. It should lower horizontal acceleration response of the building under given seismic load.
2. A predominantly translational behavior of the building.
3. No amplification of the vertical motion with respect to the ground motion.
4. A satisfactory accommodation to the large displacement that can take place.

The first criterion is obvious. Low acceleration response leads to reduced shears and overturning moments and consequently to minimum damage. The structural materials work essentially in the elastic range and always remain capable of withstanding successive shocks.

The second criterion excludes rotational motions about the principal horizontal axis of the building. The whole building then moves like a quasi-rigid body with three main consequences: firstly, drift between stories is reduced, resulting in little or no non-structural damage, secondly, the base rocking is strongly decreased which entails a lesser risk of large irregular settling in the foundation soil and lastly no significant coupling exists between the vertical and horizontal motions which enables a substantial simplification of the design.

The third criterion aims to prevent the vertical amplification which can result from the practical dispositions employed to satisfy the criteria a) and b). Considering that buildings are constructed to withstand high vertical forces, the third criterion is a minimum isolation requirement permitting vertical seismic forces to be transmitted through the structure without attenuation or amplification.

The fourth criterion concerns the building stability under large displacements that can occur during strong earthquakes. Stability is obviously a basic parameter when designing any earthquake resistant system.

3. Practical Implementation of Effective Base Isolation System

The most practical method of implementing a really effective base isolation system is to mount the building in energy absorption devices called isolators that are located between the first floor and the basement or between the first floor and the ground floor level, if no basement exists. (as in GAPEC system)

Isolators consist of laminated layers of rubber and steel plates strongly bonded together during the rubber vulcanizing process (Fig. 1). Their main feature is a relatively high stiffness in the vertical direction and around the two principal horizontal axes and a low stiffness in the horizontal plane and around the vertical axis. Lateral stiffness of isolators is currently five hundred times less than the vertical one and one hundred times less than the horizontal stiffness of the first storey concrete column; the structure of the isolators permits the separate control of horizontal and vertical stiffness. Isolators have a quasi-linear behavior upto 10% compressive strain ratio and upto 100% shear strain ratio. Thanks to special chemical composition, the rubber employed is efficiently protected against air oxygen and the steel plates are covered with highly resistant paints. Thus the isolators have a life expectancy at least as long as that of the building that they protect. Finally, in spite of the fact that isolators are strongly attached to the structure, provisions are made to change them if necessary, without excessive work.

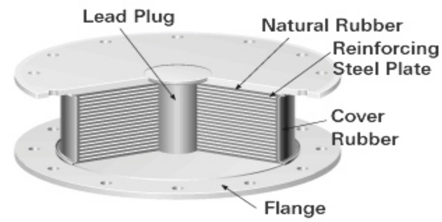

Fig. 1 Lead Rubber Bearing

4. Dynamic Characteristics of Building on Isolators

Let us see now how a building mounted on isolators meets the four basic criteria mentioned above.

1. It is well known that the natural period increases if the stiffness of the connection between the structure and the ground is decreased. This characteristic is a direct consequence of the dynamic equilibrium equations and has been utilized for some time in the field of machinery isolations. The absolute maximum acceleration response of a multiple-degree of freedom system submitted to a ground acceleration a(t) is expressed by the formula:

$$|\ddot{u}(t)|_{max} = \Sigma \alpha_j \chi_j S_{aj} \quad (1)$$

where,

$$S_{aj} = \omega_j|\text{int. 0 to t } a(\tau) \exp.[-\xi_j \omega_j(t-\tau)] \sin \omega_j(t-\tau) d\tau|_{max} \quad (2)$$

represents the spectral acceleration in the j^{th} mode, χ_j and α_j, ω_j, ξ_j are respectively the modal participation factor, the natural circular frequency and the equivalent viscous damping ratio of the j^{th} mode. As far as isolation system is concerned, we have to consider two distinct type of acceleration response spectra in view of the predominant natural periods.

Since we have observed that by decreasing the stiffness of the supporting elements we increase the natural periods, we have to design the isolators accordingly. The lateral stiffness of the isolators may be expressed as:

$$K_x = \Sigma GA/L_c \quad (3)$$

where G is the shear modulus of rubber, A is the cross – sectional area of rubber, L_c the total thickness of rubber. The summation is extended to the number N of isolators. A is determined by the maximum permissible compression stress σ under static load and G depends on the quality of the rubber.

2. The low lateral stiffness of isolators brings about rigid body modes of vibration. Indeed let us bear in mind that the first two natural frequencies of a free-free structure (a simple beam for instance) are zero, the first mode corresponding to a rigid body translational motion and the second mode to a rigid rotational motion. A structure with low stiffness supporting elements tends to behave like a free-free structure and consequently, we have to wait for a first mode with predominant rigid translation and a second one with a predominant rigid rocking motion. Three basic parameters control the behavior of a building mounted on isolators:
   a. The slenderness ratio e, which is the ratio between the height of the building and the dimension in plan parallel to the displacement.
   b. The mean horizontal stiffness K_M which is the arithmetic mean of the story stiffness and,
   c. The horizontal stiffness K_{IX} of the isolators.

3. The ability to independently control the lateral stiffness of isolators without affecting the vertical stiffness finds another application that is related to the vertical response. It is possible to design the vertical stiffness K_{IZ} of the isolators so that the fundamental period in the vertical direction is low enough to prevent amplification; this dynamic aspect of the design meets the requirement that necessitates high vertical stiffness to limit the vertical static deflection. In addition, damping introduced by isolators, nearly 6% of critical, largely contributes, in any situation, to reduce the vertical response.

4. Displacement at the base of the building is roughly proportional to the square of the first natural period. Consequently, large displacements may be associated with low acceleration that result from high natural periods. The behavior of a building mounted on isolators through the energy dissipation concept. In a rigidly fixed building, the seismic energy input resulting from the ground motion is mainly dissipated by a general elasto – plastic distortion of the structure; on the contrary, if the building is mounted on isolators, the seismic energy is dissipated essentially through the lateral displacement of the structure; the higher the first natural period, the slower is the displacement.

We can obtain an approximate measure of stability under large displacements by the following considerations. Let W and H represent the weight and height of the building, S_o be the base shear and U_x the first floor lateral xx displacement. If the building moves like a rigid body, the base moment around the horizontal axis yy may be written as:

$$M_y = S_o \; H/2 + W_{ux} \qquad (4)$$

or, observing that, with an effective isolation system, S_o is a fraction β of W, for instance $\beta < 0.5$;

$$M_y = W \; (\beta H/2 + U_x) \qquad (5)$$

It is easy to verify that in all practical applications, U_x is negligible compared with βH/2. Consequently, the load eccentricity resulting from large displacement has no influence on the building stability.

If the first floor is stiff enough, the isolators are rigidly connected together and work as a single unit to resist the moment. The additional compressive stress in isolator may be expressed as:

$$(\sigma_1)_I = M_y \; a_{xi} \; / \; I_y \qquad (6)$$

in which a_{xi} is the distance of the isolator (i) from the vertical plane as defined by yy axis and the centre of mass, I_y is the quadratic moment of inertia of the isolators with respect to the yy axis of the building. The total compressive stress in the isolator (i) may be written as:

$$(\sigma)_I = Q_i \; / \; A_i + (\sigma_1)_I \qquad (7)$$

where Q_i is the vertical load on the isolator (i) and A_i the rubber cross – sectional area.

If $(\sigma_a)_I$ is the buckling stress on the isolator (i), the ratio $(\sigma_a)_i/\sigma_i$ represents a measure of the local stability at point i. If the calculations are made for each isolator, a measure of the general stability of the structure may thus be obtained.

5. Example of Application of the Base Isolation System

The 300 bed Bhuj Hospital that claimed 176 lives when it collapsed during the major January 2001 Gujarat Earthquake is studied. This was the first new building in India to be fitted with earthquake – resistant NZ developed base isolation technology. Eventually, 280 lead rubber bearings were installed in the structure. The hospitals base isolation design and bearings have been provided with the assistance Earthquake Engineering NZ members.

With the assistance of the New Zealand Government and support of the Earthquake Engineering NZ cluster we was able to identify the reconstruction of the Bhuj hospital as a suitable project for New Zealand's earthquake engineering assistance. They recommended that the replacement hospital be fitted with New Zealand developed base isolation lead rubber bearings. This robust technology is well-suited to construction styles in India. The New Zealand Government contributed $ 150,000 to the cost of the project base-isolation feasibility study and design work as part of the initial disaster recovery stage. The Indian Prime Minister's Relief Fund funded the hospital construction, including the cost of the Robinson Seismic Ltd bearings.

Fig. 2 Lead Rubber Bearing designed by Bill Robinson

Fellow cluster members Holmes Consulting Group and Dunning Thornton Consultants, with the bearings manufactured and supplied by Robinson Seismic Ltd undertook the specialist computer-based earthquake-resistant base-isolation building design work in Wellington. Cluster member Bill Robinson invented the lead rubber bearing technology.

The Creative Capital Cluster of the achievement of rebuilding the new Bhuj hospital within two years of the earthquake by India's leading architects, engineers and construction firm working with the assistance of New Zealand's specialist earthquake engineering expertise. Architect Uday Pattanayak of EFN Ribeiro Associates, New Delhi, and Structural Engineer Kamal Sabharwal, has led the Indian design team for the hospital. The construction company was India's largest, Larsen & Toubro. New Bhuj Hospital completed with Earthquake Engineering NZ technology is reputed to be able to stand a force of 10 tremor on the Richter scale.

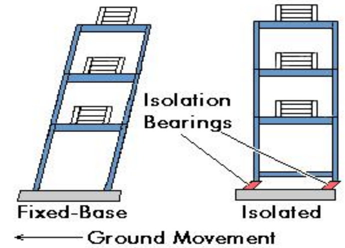

Fig. 3 Seismic behavior of building mounted without and with isolator.

6. Conclusion

If a Base Isolation System satisfies the four basic requirements, it can solve a great variety of earthquake protection problems with greatly increased security and at generally cheaper costs than classical strengthening techniques. A full protection may be obtained when it is required, due to the fact that the isolators and the structural materials of the building mounted on isolators work in the elastic range only.

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